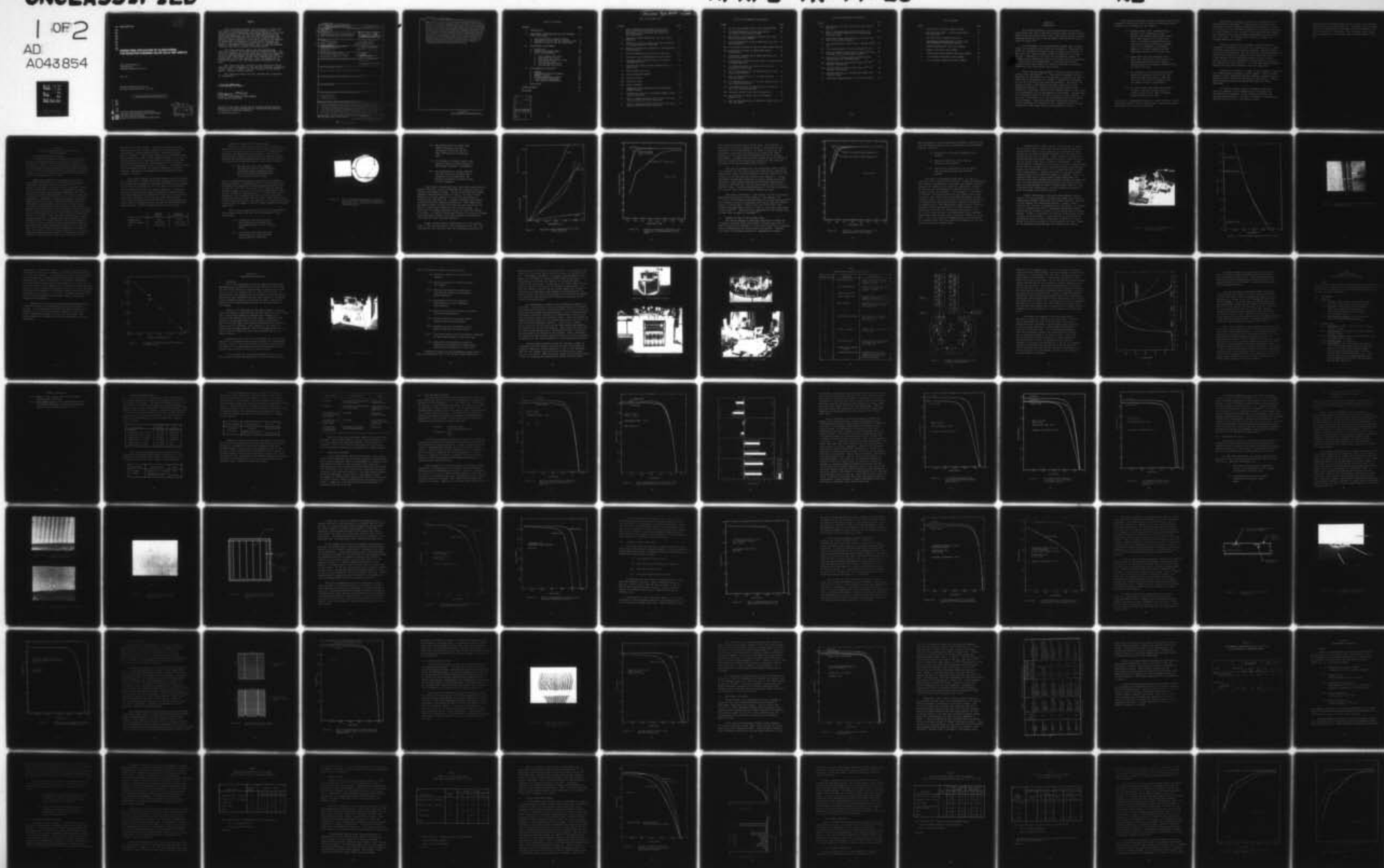
AD-A043 854 SIMULATION PHYSICS INC BEDFORD MA F/G 10/2
STRESS FREE APPLICATION OF GLASS COVERS FOR RADIATION HARDENED --ETC(U)
MAY 77 A R KIRKPATRICK, W S KREISMAN F33615-74-C-2001

UNCLASSIFIED AFAPL-TR-77-28 NL

1 OF 2
AD
A043854



AFAPL-TR-77-28

(10)

B.S.

STRESS FREE APPLICATION OF GLASS COVERS FOR RADIATION HARDENED SOLAR CELLS AND ARRAYS

SIMULATION PHYSICS, INC.
PATRIOTS PARK
BEDFORD, MASSACHUSETTS 01730

MAY 1977

TECHNICAL REPORT AFAPL-TR-77-28
Final Report for Period January 1974 – July 1976

AIR FORCE AERO PROPULSION LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

NOTICE

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, of conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

This Final Technical Report has been submitted by Simulation Physics, Inc. under Contract F33615-74-C-2001. The effort is sponsored by the Air Force Aero Propulsion Laboratory, Air Force Systems Command, Wright-Patterson AFB, Ohio under Project 3145, Task 314519 and Work Unit 31451948 with Lt. Cecil Stuerke/POE-2 as Project Engineer. Allen R. Kirkpatrick of Simulation Physics, Inc. was technically responsible for the work.

This report has been reviewed by the Information Office (ASD/OIP) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

Cecil Stuerke

Cecil Stuerke, Lt. USAF

Joseph F. Wise

Joseph F. Wise/Technical Area Manager
Solar Energy Conversion

Copies of this report should not be returned unless return is required by security considerations, contractual obligations, or notice on a specific document.

AIR FORCE/56780/25 August 1977 — 200

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: AFAPL-TR-77-28	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): STRESS FREE APPLICATION OF GLASS COVERS FOR RADIATION HARDENED SOLAR CELLS AND ARRAYS,	5. TYPE OF REPORT & PERIOD COVERED: FINAL TECHNICAL REPORT, January 1974 — July 1976,
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): Allen R. Kirkpatrick, Wallace S. Kreisman, John A. Minnucci	8. CONTRACT OR GRANT NUMBER(s): Air Force Contract F33615-74-C-2001
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Simulation Physics, Inc., Patriots Park, Bedford, MA 01730	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 31451948
11. CONTROLLING OFFICE NAME AND ADDRESS: Air Force Aero Propulsion Laboratory, Wright-Patterson AFB, Ohio 45433	12. REPORT DATE: May 1977
	13. NUMBER OF PAGES: 105
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report): Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Silicon Solar Cells
Integral Covers
Electrostatic Bonding

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes a two and one half year program to develop a practical integral protective cover for silicon solar cells. The report discusses the electrostatic bonding process, methods for its utilization and selection of a satisfactory glass cover material for use with the process. Excellent results have been achieved in demonstrating integral covers 150μ to more than 500 μ thick onto several types of 2 x 2 cm cells with SiO_x or Ta_2O_5 anti-reflective coatings. The most difficult problem in applying electrostatically

micrometers

DD FORM 1473 (1 JAN 73) EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

micrometers

390900

bonded covers to silicon solar cells involves the raised metallization pattern on the otherwise essentially planar cell surface. Cover glasses can either be plastically deformed around the material pattern or can be mechanically grooved to accept the grid material. The plastic deformation approach requires higher bonding process temperatures, to as high as 600°C, but should be more practical in production. Representative integral cover cell samples have exhibited excellent stability under environmental testing. An automated facility has been constructed to demonstrate production feasibility for application of integral covers. Cells covered using the automated facility have exhibited some contact integrity problems which have been identified as associated with the presence of an oxidizing atmosphere during bonding. Facility correction will be required. The electrostatic bonding process shows promise for major technical and economic advantages over conventional glued covers.

TABLE OF CONTENTS

PRECEDING PAGE BLANK - NOT FILMED

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Continued)

LIST OF ILLUSTRATION (Continued)

LIST OF TABLES

SECTION I

INTRODUCTION

This report describes a thirty month effort from January 1974 through June 1976 to develop electrostatically bonded integral glass covers for silicon solar cells. Some of the content has been discussed previously in an Interim Report, AFAPL-TR-75-54, distributed in August 1975.

The development of electrostatically bonded (ESB) integral covers is considered to have been very successful. Technology now exists for integrally attaching covers of almost any thickness to many solar cell types including standard production and "violet" designs. Compatibility with high cell performance, absence of residual stress effects and ability to tolerate severe environmental conditions have been demonstrated. Electrostatically bonded integral covers show promise for definite technical and economic superiority over conventional glued covers.

There have been many attempts to develop integral covers by several other approaches[1-10]. These earlier programs involved deposition of the protective cover material in molecular or particulate form by evaporation, by a number of sputtering techniques, by frit and fuse and by some modified processes. Each effort was found to result in unacceptable technical capabilities and/or impractical economics. Technical deficiencies generally were directly or indirectly related to high residual stress in the covers or to degradation of cell performance by the process. Although many of the programs sought to use fused silica as a cover material, in each case a redirection to a less satisfactory material was found to be necessary. Most of the candidate methods were found to involve inherently low deposition rates, expensive facilities and substantial yield losses leading to noncompetitive costs.

Based upon the findings of earlier integral cover efforts, a number of conclusions could be drawn which defined starting rationale for the program of this report:

(i) Although fused silica (amorphous SiO_2), because of its outstanding optical, physical and chemical stabilities, would be the best material for a solar cell cover, its physical characteristics are such that no existing process or process likely to be developed can adequately deposit it in thick integral form and unstressed condition on a silicon cell.

(ii) Among other available candidate cover materials, Corning type 7070 borosilicate glass possesses satisfactory combined physical,optical and chemical characteristics for solar cell use.

(iii) The economics of all molecule-by-molecule deposition processes are such that production volume costs goals of less than \$0.10 per cm^2 for thick integral covers are almost certainly unachievable.

(iv) In order to meet cost goals for integral covers, a bulk application process in which the entire cover mass is attached simultaneously must be used.

The choice of electrostatic bonding to attach slides of Corning 7070 glass directly to cell surfaces was a natural and logical consequence of the facts listed above.

Electrostatic bonding is actually an electrostatic field assisted sealing technique[11] which avoids all the major disadvantages of other candidate integral cover processes. Slides of 7070 glass of any available thickness can be integrally bonded in to a cell surface in five minutes or less under moderate temperature conditions that need not degrade performance of most solar cell structures. The covered cells exhibit no evidence of residual mechanical stresses.

During the period of the program, integral covers were successfully attached to most solar cell structures with a number of contact types and antireflective coatings. Textured surface cells were not considered. The most difficult problems encountered involved the mechanics of applying a flat glass cover sheet to a cell surface with a raised metallization pattern and also involved effects of the experimental bonding ambient conditions upon stability of cell contacts. It is believed that satisfactory methods and corrective procedures have been identified.

Throughout the program, a number of environmental evaluations were conducted upon integrally covered samples. Tests included thermal cycling, temperature-humidity storage, vacuum-ultraviolet exposure, proton irradiation and electron irradiation. Integral covers exhibited ability to perform well under all these conditions.

In order to produce sufficient numbers of ESB cover cells for purposes of this program and for requirements of anticipated test programs, a pilot production facility was designed and constructed. The unit is capable of automatically applying covers to 60 2 x 2 cm cells per hour.

Economic projections based upon the use of such a unit indicate that production costs should be low. Production of a thin sheet form of 7070 glass might allow glass cost to be reduced to less than \$0.01 per cm^2. Total cover cost, including glass cover, sizing, bonding, yield and profit could be less than \$0.10 per cm^2.

SECTION II
PRELIMINARY CONSIDERATIONS FOR ESB INTEGRAL COVER DEVELOPMENT

1. THE ELECTROSTATIC BONDING PROCESS

The method of electrostatic bonding is based upon a proprietary field-assisted glass to metal sealing technique[12]. The mechanics consist of correctly positioning a glass slide on the surface to which it is to be bonded, raising temperature until the glass becomes ionically conductive and then applying voltages so as to first set up electrostatic forces sufficient to bring the bonding surfaces into intimate contact and then to move reactive ions to the interface to create a bond.

Temperatures needed for the process are not critical. Developmental bonding under this program has been performed at temperatures from below 450°C up to as high as 570°C. No variation of the quality of the bond itself is observed. However, at lower temperatures the surfaces to be bonded must be able to come into good contact, while at higher temperatures the strong electrostatic forces cause deformation of the glass to occur during the process so that initial surface profiles need not be entirely complementary. Regardless of temperature employed, the bonding mechanisms require only that a condition of ionic conductivity be established in the glass, usually by creation of mobile alkali ion species from dissociation of Na_2O and Li_2O. When a negative voltage is then applied to the glass, transfer of positive ions away from the glass/cell interface occurs and produces a shallow polarized positive ion depleted layer in the glass at points of contact with the cell. As a result, almost the entire applied voltage, usually several hundred volts, is dropped across this interfacial layer. Adjacent to points of contact, wherever there is a gap between the cell and the glass, the applied voltage appears across the gap and can produce very intense electrostatic forces acting to close the space. The forces can cause plastic deformation of the glass to occur, more easily of course at higher temperatures. Once the cell and glass surfaces have been brought into close contact, a bond is produced by reaction of free oxygen ions in the glass with the

material of the cell surface. Glasses will permanently bond directly to silicon, to SiO_x or Ta_2O_5 and most other solar cell antireflective coating materials and to some contact metals such as aluminum. A bond to the contact grid is unnecessary and does not take place with a silver surface contact. It is only the extreme surface of the solar cell which is involved in the bond and no change results in the effectiveness of the AR coating relative to its performance with a glued cover. The bonding process is not reversible and once the bond is completed, it cannot be released. Strength of the bonded interface exceeds the yield strength of silicon.

Total times required for the ESB process need not be longer than a few minutes. Bonding conditions developed and used during this program have depended upon whether the cover glass was mechanically grooved to provide for the cell contact grid or whether plastic deformation around the grid was desired. In addition to the time required for the actual electrostatic bonding process, some additional period is required for heating the cell and cover to process temperature and for cooling again after bonding. These times have ranged from less than one to several minutes depending upon the bonding facility utilized and the process parameters selected. Typical conditions have been as follows:

	Grooved Covers	Plastic Deformation
Temperature	450°C	560°C
Applied Voltage	1200 Volts	1200 Volts
Time	1-3 Minutes	3 Minutes

2. SELECTION OF GLASS FOR THE INTEGRAL COVER

Choice of the glass for an integral cover is critical, perhaps even more so with ESB than other methods. Fused silica is by far the best material for glued covers but it cannot be considered for the ESB integral cover because it lacks one key characteristic: expansion coefficient match to that of silicon. Experience during this program has shown that the starting point for selection of the ESB cover material must be the following:

(i) The glass must have a net expansion characteristic between room temperature and bonding process temperature (450-560°C) which closely matches expansion of silicon over the same range.

Figure 1 illustrates the result of violation of the expansion match requirement. The photograph shows a slide of Corning 0211 microsheet with substantially higher expansion coefficient than silicon (59×10^{-7} $°C^{-1}$ vs 30×10^{-7} $°C^{-1}$) which was electrostatically bonded to a bare silicon wafer at approximately 500°C and then returned to room temperature. As cooling took place, the microsheet tried to contract more than the silicon and severe distortion of glass and wafer began to occur. When stress in the silicon reached yield level, the surface of the silicon was torn from the wafer and left bonded to the still highly stressed and distorted glass slide.

After matching expansion characteristics, the requirements on the glass are less rigid but still not necessarily easily accomplished:

(ii) The material must exhibit close to 100% transmission of photons over wavelengths between 0.3 and 1.2 micrometers.

(iii) The material must resist darkening under exposure to ultraviolet and ionizing particle radiations.

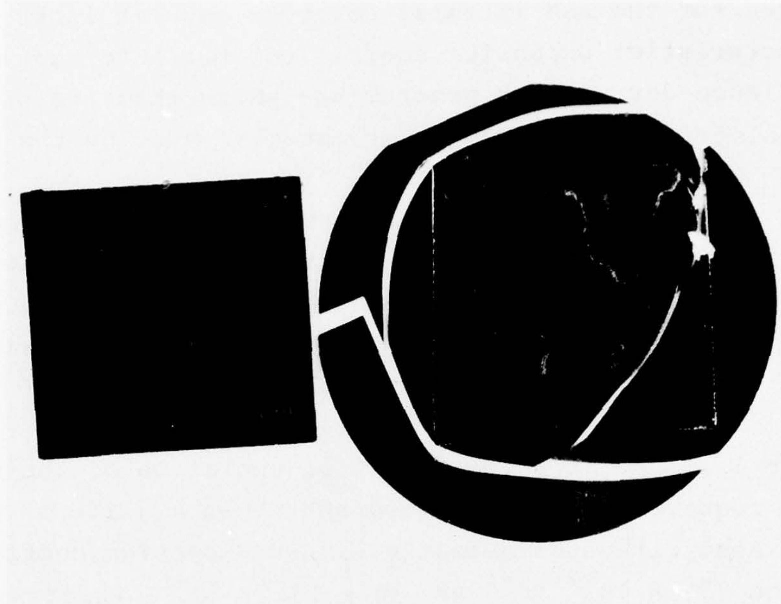


Figure 1. 0211 Microsheet Slide Bonded to Silicon Wafer with Slide and Silicon Surface Torn from Wafer Due to Stresses Upon Return to Room Temperature.

(iv) The material must be stable under ambient atmosphere and space environment conditions and also under conditions of the ESB process.

(v) For purposes of thermal control, the material should be highly emissive at wavelengths exceeding 5 micrometers.

(vi) For optimization of optical coupling into the cell using available anti-reflective coating materials, the material should have refractive index as low as possible.

Glued covers on spacecraft solar cells have usually been of Corning 7940 fused silica or sometimes 0211 Microsheet for low radiation environment missions. As can be seen from the thermal expansion characteristic curves of Figure 2, neither of these materials is closely matched to silicon and they cannot be considered for ESB cover use. A number of borosilicate glasses do have satisfactory expansion coefficents. From commercially available products, Corning 7070 glass has been selected on the basis of overall best suitability for integral covers. In particular its thermal expansion behavior is very well matched to silicon. It should be noted that several of the earlier integral cover development efforts using other methods also identified 7070 glass as a best available material.

Figure 3a shows optical transmittance of a 300 μm thick slide of 7070 glass initially, after irradiation with 10^{16} 1 MeV electrons per cm^2, and then after the approximate equivalent of

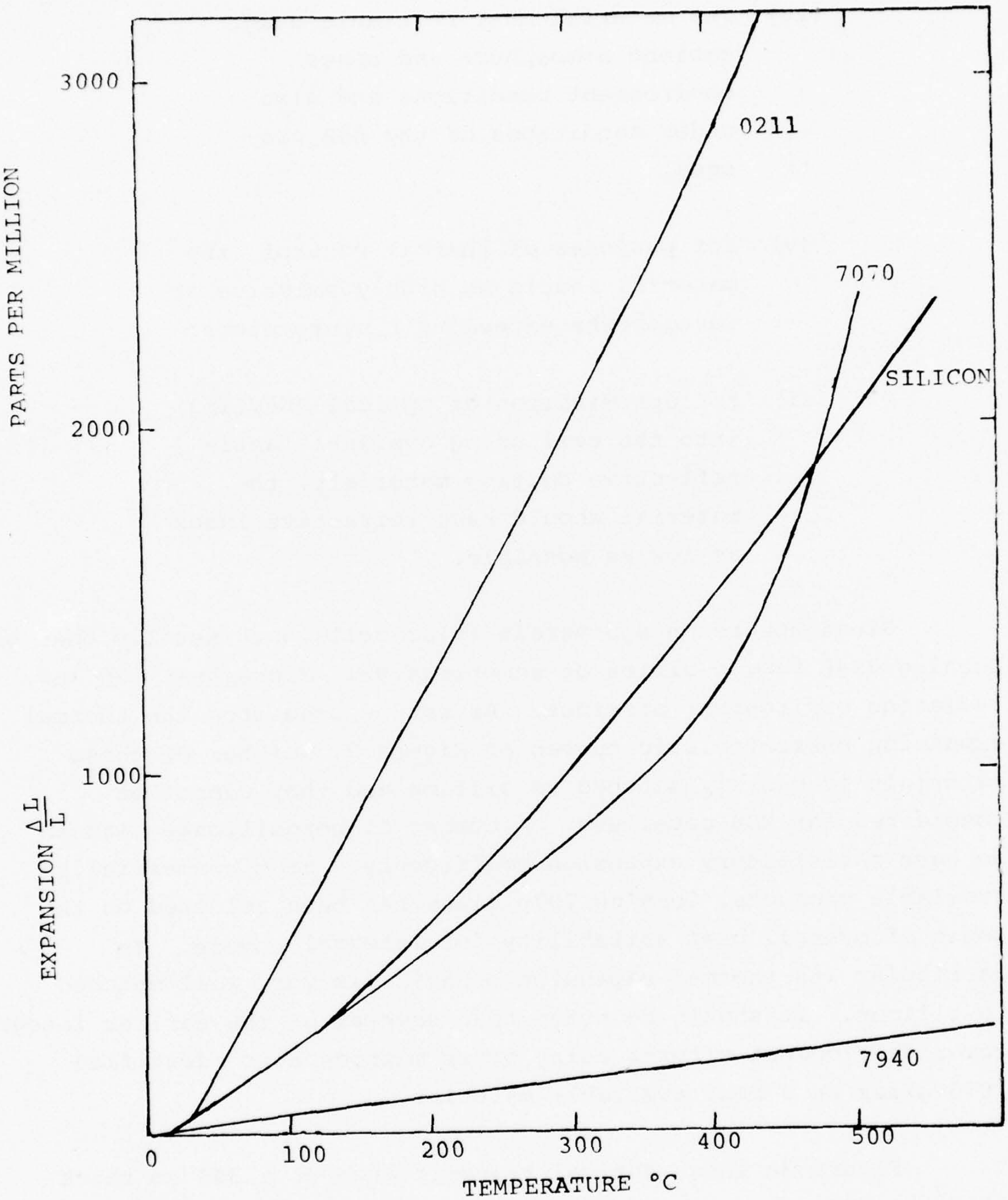


Figure 2. Expansion Versus Temperature for Cover Glass Materials

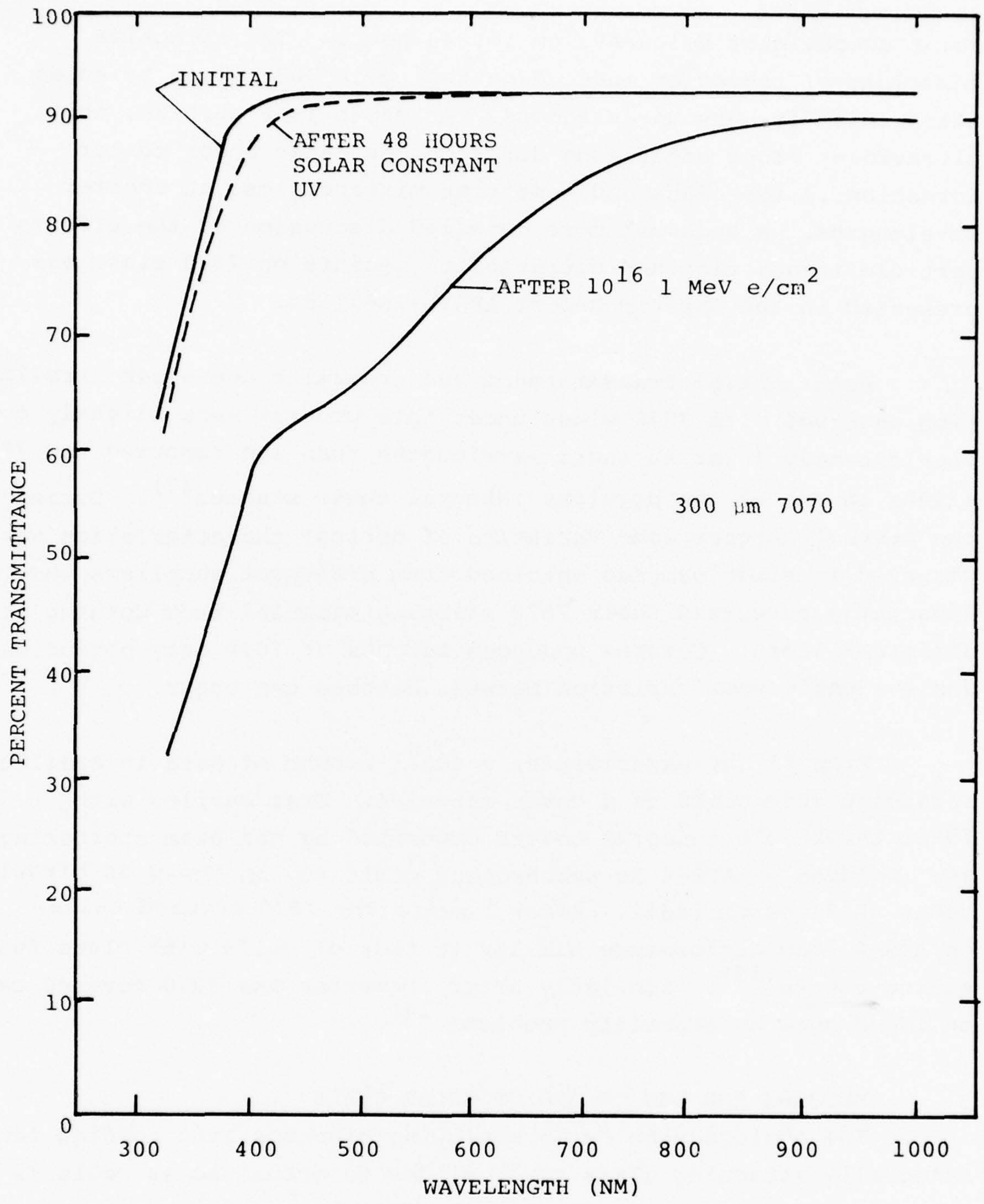


Figure 3a. Effects of Electron Irradiation then Bleaching on Transmittance of 7070 Glass

solar ultraviolet below 400 nm for 48 hours. The effective bleaching of radiation induced darkening in 7070 glass by solar ultraviolet is very advantageous. As shown in Figure 3b, the ultraviolet alone after long duration can cause color center formation in the glass and some transmittance loss at shorter wavelengths. A somewhat more detailed discussion of the effects of particle irradiation and ultraviolet exposure on 7070 glass was presented in the Interim Report AFAPL-TR-75-54.

Both initial transmittance and transmittance after irradiation observed with 7070 glass under this program were slightly but significantly lower at short wavelengths than was reported for 7070 slides in one of the previous integral cover studies(7). During the present program some variation of optical characteristics was observed in slide samples obtained from different suppliers who apparently purchased their 7070 starting material from Corning at different times. Corning produces batches of 7070 only periodically and evidently some variation between batches can occur.

From flight experiments, a small amount of data is available regarding 7070 glass as a cover material. Test samples with 75 μm thick 7070 integral covers deposited by ion beam sputtering(8,9) are included on ATS-6 in synchronous orbit and on IMP-H in circular orbit at 31 earth radii. After 2 years the 7070 covered cells on ATS-6 show performance similar to that of cells with glued fused silica covers(13). Similarly after 48 months the 7070 covered cells on IMP-H show no stability problems(14).

3. METHODS FOR USE OF ESB ON SOLAR CELLS

The obvious problem in employing electrostatic bonding for integrally attaching glass cover slides to actual solar cells is that the typical cell surface is not flat but rather has an irregular profile determined by the front contact grid pattern. Standard use of ESB is for bonding together of complementary surfaces.

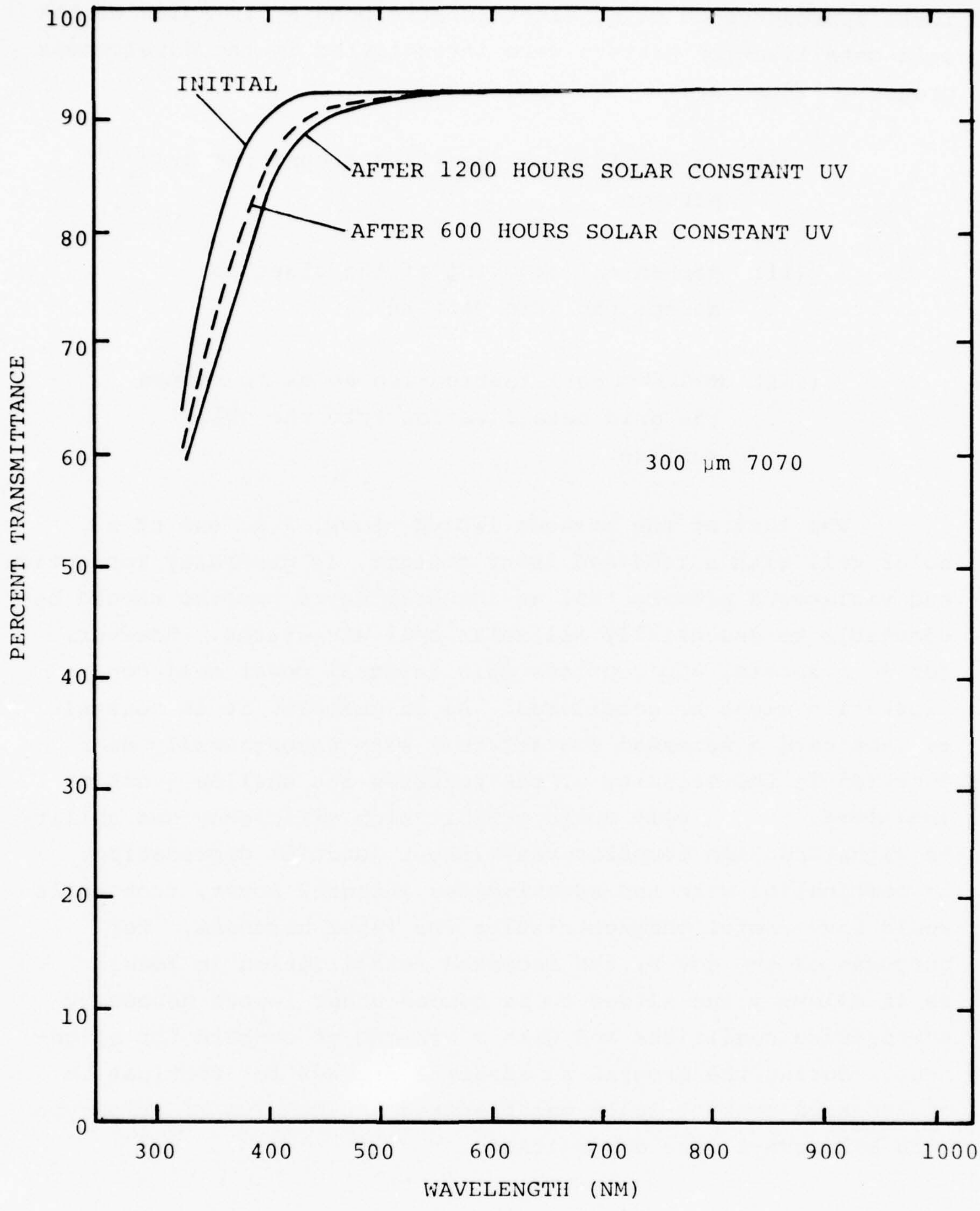


Figure 3b. Effect of Ultraviolet Exposure on Transmittance of 7070 Glass

Three approaches to using electrostatic bonding in spite of the cell metallization pattern were investigated in the development program. These are:

(i) Deformation of the glass around the grid pattern.

(ii) Mechanical grooving of the glass to accept the grid pattern.

(iii) Modified cell fabrication so as to recess the grid metallization into the cell surface.

The last of the methods listed above, i.e. use of a solar cell with a recessed front contact, is generally impractical and violates a premise that an integral cover process should be adaptable to essentially all solar cell structures. However, for some special applications this integral cover cell configuration might be considered. As an example, it is possible to fabricate a recessed contact cell with exceptionally deep junction in the vicinity of the recesses and shallow junction elsewhere. Such a cell could exhibit high efficiency and ability to withstand high temperatures without junction degradation. In combination with the adhesiveless integral cover, such cells would have useful characteristics for laser hardness. For purposes of the cover, the recessed metallization is ideal as it allows plane slides to be bonded under lowest necessary temperature conditions and with a minimum of concern for alignment. During the program an adequate process for fabrication of recessed contact cells was prepared and samples of this type with ESB covers were demonstrated.

Introduction of shallow grooves into the cover to accept the cell front contact finger grid can be relatively easily performed and has been a useful technique for developmental work. Grooves can be formed by thermal deformation of the glass or by mechanical scoring or grinding. Figure 4 shows a fixture which allows precisely positioned grooves for parallel grid lines to be cut into glass slides using a diamond cutting blade. A single blade requires a separate cut for each grid line but a ganged blade can be used for introducing all necessary grooves simultaneously. Usually the grooves are cut 25 to 50 μm wider than the cell grid finger metallization. Grooved covers can be used with minimum bonding conditions but careful alignment is required. Also it is important that cells to have grooved covers should have consistently positioned reproducible grid metal pattern and should not have any stray metallization residue over their active surfaces. Among the disadvantages of using a grooved cover, even if it can be prepared very inexpensively, is that protective thickness of glass is reduced at the grid locations.

Plastic deformation of the cover glass material around features of the cell surface including the contact grid requires temperatures somewhat higher than the minimum conditions necessary to bond together flat well-mated surfaces. Figure 5 shows viscosity as a function of temperature for 7070 glass. As temperature is increased above 450°C, substantial deformation occurs readily during the three minutes or less normally used to produce bonding. Figure 6 illustrates the behavior, which results in the vicinity of a grid finger. On each side of the grid finger an unbonded gap occurs in which interference fringes can be seen. Beyond this region the glass is fully bonded to the cell. Width of the unbonded gap depends upon grid thickness and bonding

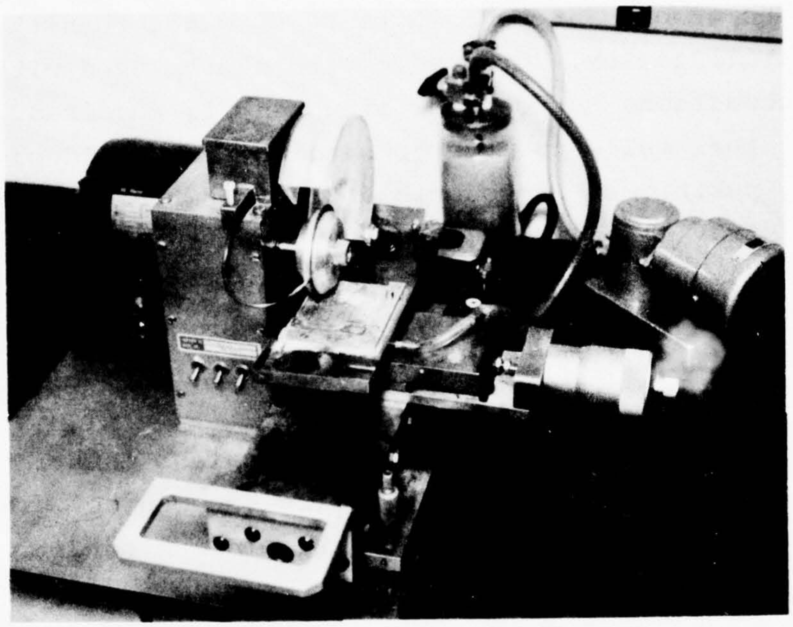


Figure 4. Diamond Cutting Blade Facility for Cover Grooving.

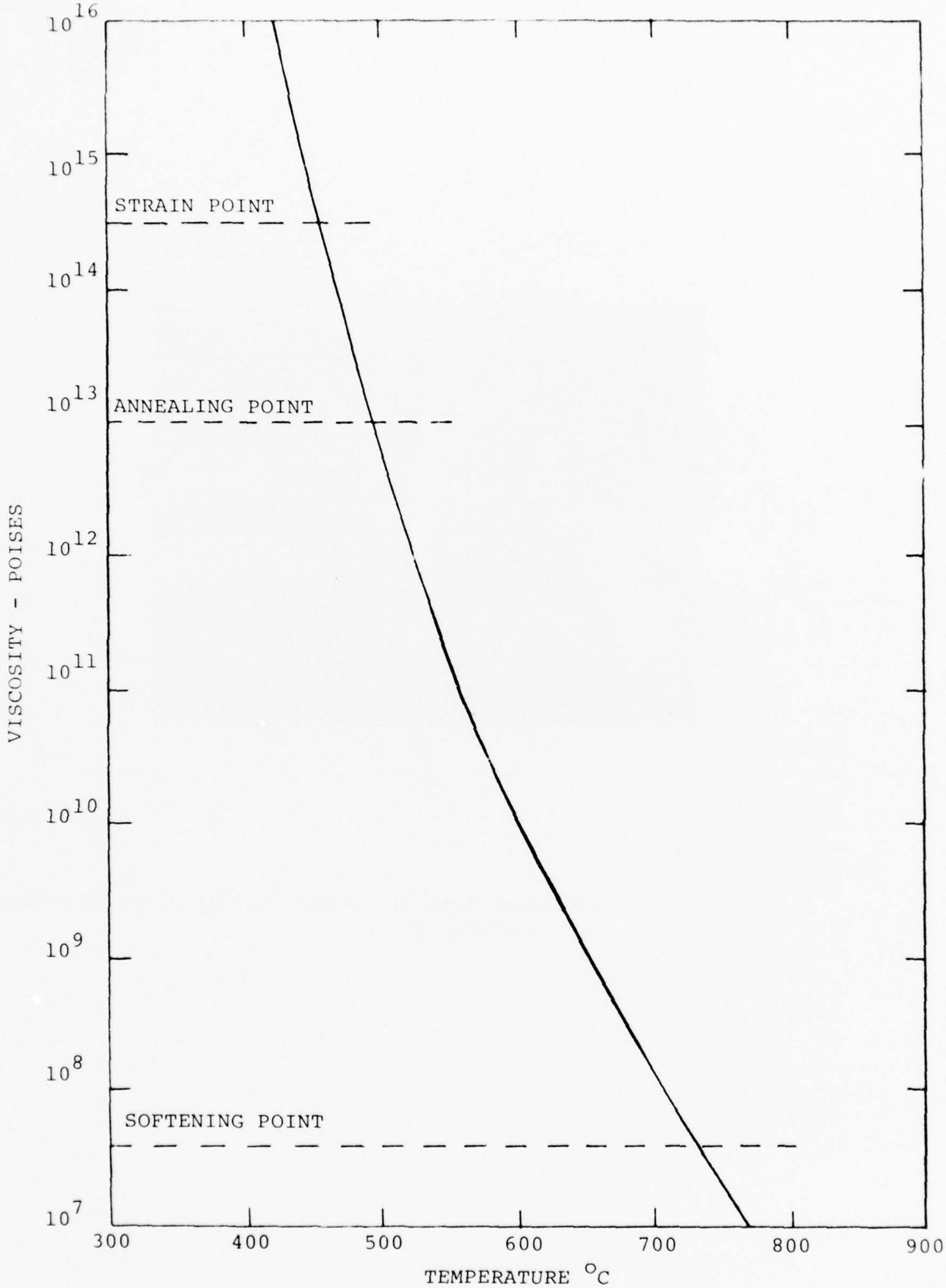
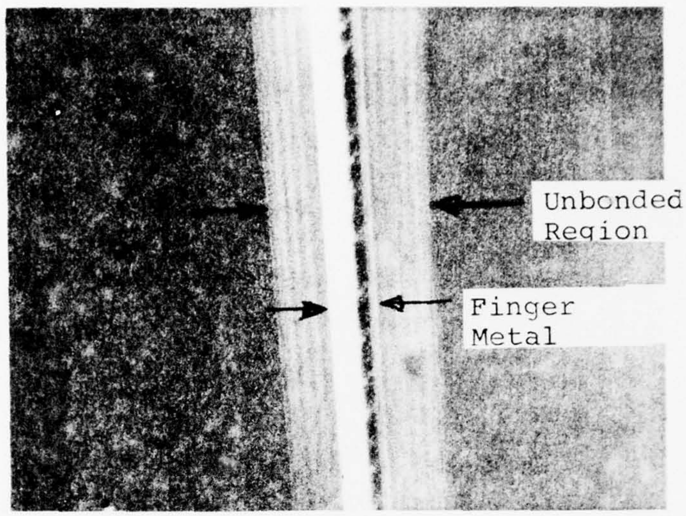


Figure 5. Visosity Versus Temperature for 7070 glass



45X

Figure 6. Unbonded Region Around Finger Grid-Plastic Deformation Cover.

temperature. Gap width is plotted, in Figure 7, against bonding temperature for a series of bonds to cell samples with controlled 2 μm thick grid fingers. At a temperature in the vicinity of 560°C, the gap disappears. Similar results are obtained with thicker metallization. However deformation of the glass is produced by the electrostatic forces and if grid thickness is too large or if grid lines are too close together, the slide may not touch the cell surface in which case the electrostatic forces will not be initiated. The problem was avoided in the present program by maintaining grid thickness on most cells to 3 μm or less. A general solution could involve slight preshaping of the glass surface in a separate operation before bonding.

Recessed contact cells, grooved covers and plastically deformed covers were all investigated during the experimental program. It has generally been concluded that with proper preparation it will be possible and most convenient to use the plastic deformation approach on almost all cell types. Production methods can probably be limited to variations of plastic deformation.

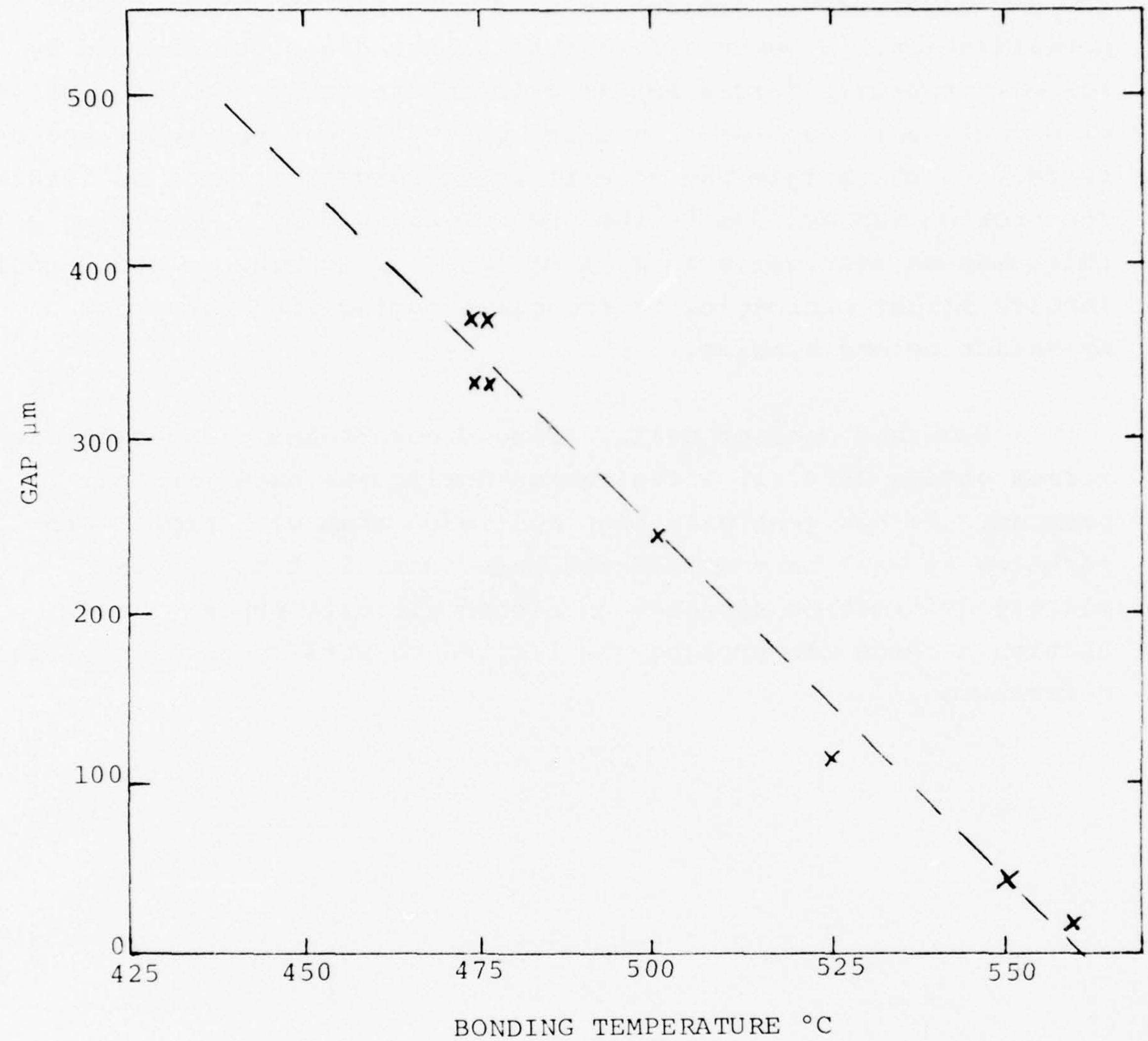


Figure 7. Unbonded Gap Versus Bonding Temperature - 2 μm Thick Grid

SECTION III
EXPERIMENTAL DEVELOPMENT

1. FACILITIES

Most of the experimental ESB work under this program was performed using two electrostatic bonder facilities. The first unit was totally manual and could be used to apply covers to one cell at a time at a maximum rate of a few cells per hour. A second facility was designed and constructed to allow for process optimization and reproducibility and, when necessary, to provide a pilot production capacity of 60 cells per hour. This pilot production unit became operational only in the last months of the program.

Figure 8 is a photograph of the manual bonder. Operation starts by loading a solar cell and correctly positioned cover glass onto a vacuum chuck pedestal electrode then lowering a top electrode into contact with the cover glass. A preheated tube furnace is raised around the cell and cover by motor drive. When the cell and cover reach bonding temperature, the timed high voltage cycle is initiated. Upon completion, the furnace is lowered and the sample removed. The unit includes provision for some control and selection of the gas environment during the bonding process.

Experimental work with the manual bonder has involved many variations of fixtures, mechanics and technique for electrostatic bonding. Design of the pilot production facility was based upon the results of this experience and reflects those methods considered best suited for a solar cell cover process.

It was decided that an automated bonder facility to be used for both process development and for pilot production would

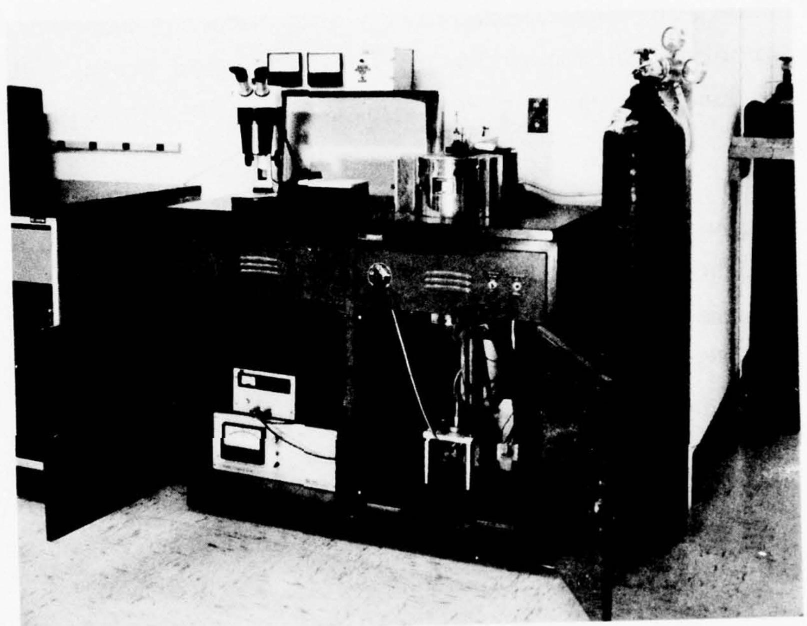


Figure 8. Manual Bonder Facility

have to include the following characteristics:

(i) Ability to operate at less than full capacity.

(ii) Ability to operate in manual and automatic modes.

(iii) Provision for operator intervention and flexible control during developmental operation.

(iv) Elimination of need for operator participation in pilot production mode operation.

(v) Ability to accept solar cells of different sizes and configurations.

(vi) Flexible selection of process temperatures and high voltage cycles.

(vii) Automatic precise reproducible alignment of solar cell and cover glass.

(viii) Continuous operation with controllable commitment of cells under process at any given time.

(ix) Scale up to full production should be practical by construction of more bonders rather than by redesign to a larger unit.

A specific objective of the development of ESB covers is that, in production, cost of the integral cover should be a

small fraction of the value of the solar cell. In this case, yield losses will have major impact upon actual costs of integral covering. Consequently, because it is possible that something can go wrong in an automatic or nearly automatic mode of operation, it is advantageous to minimize the number of cells actually being risked at any given time. In this way a very small number of cells would be ruined in the event of an accident or malfunction. To meet this objective and to keep the bonder compact and to make it possible for an optional single operator to closely monitor the entire process, the bonder was designed using a continuous assembly line approach involving sequential operations performed around a circular processing table.

The photographs in Figures 9 and 10 show major assembly of the bonder. Basic design of the unit involves the use of moveable high temperature pallets to hold aligned solar cells and covers and transport them through the bonding process. Up to sixteen pallets are mounted around the outside of an intermittently rotating circular horizontal table (the carrousel plate). Every 60 seconds the carrousel plate steps 22.5° to transfer each pallet from one to the next of sixteen processing stations. A solar cell is loaded onto a pallet at the first station and then removed approximately 16 minutes later at the final station. Major operations take place at fixed process stations while the carrousel plate is stationary for approximately 45 seconds of every minute. Table 1 describes the function of each process station and Figure 11 gives a schematic presentation of the total procedure for pilot production operation.

Normal bonding procedure starts with loading a number of precleaned cells and covers, up to 500 of each, into respective dispenser cassettes. During operation a cell is first dispensed from the cell cassette and guided into the bottom of an alignment jig on a pallet. When the pallet rotates to the second station, a cover is dispensed and automatically guided into the correct

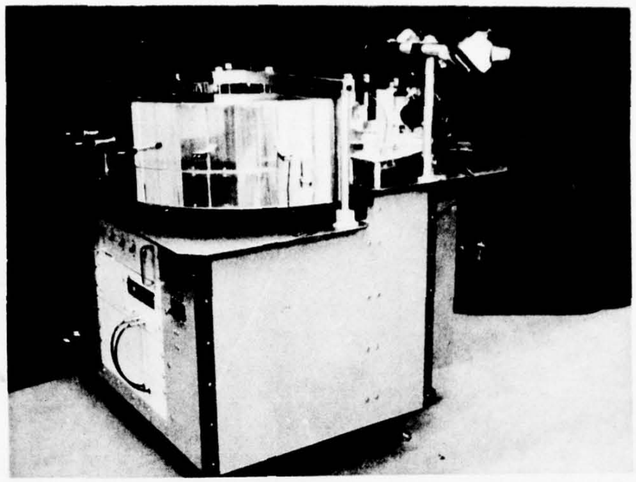


Figure 9a. Pilot Production Bonder

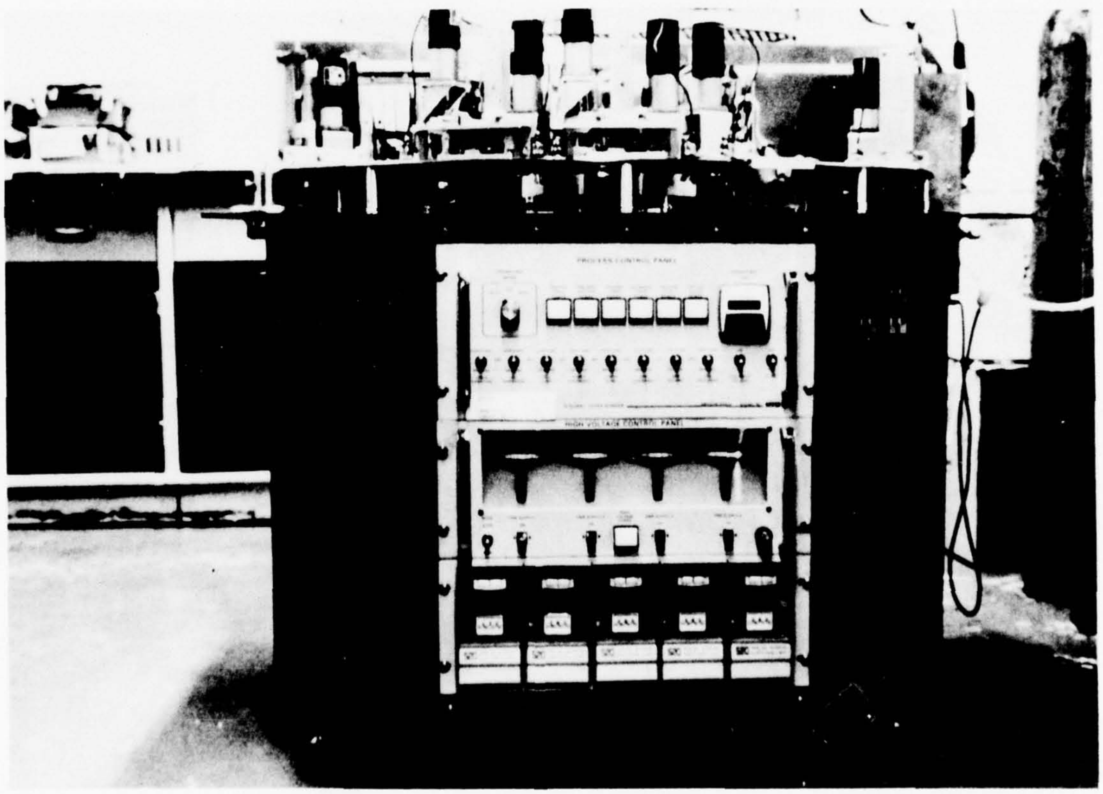


Figure 9b. Control Console

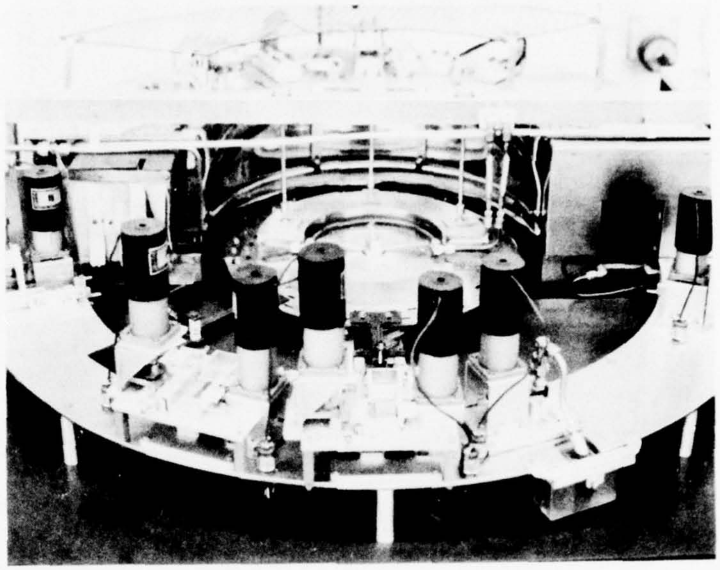


Figure 10a. Carrousel Plate

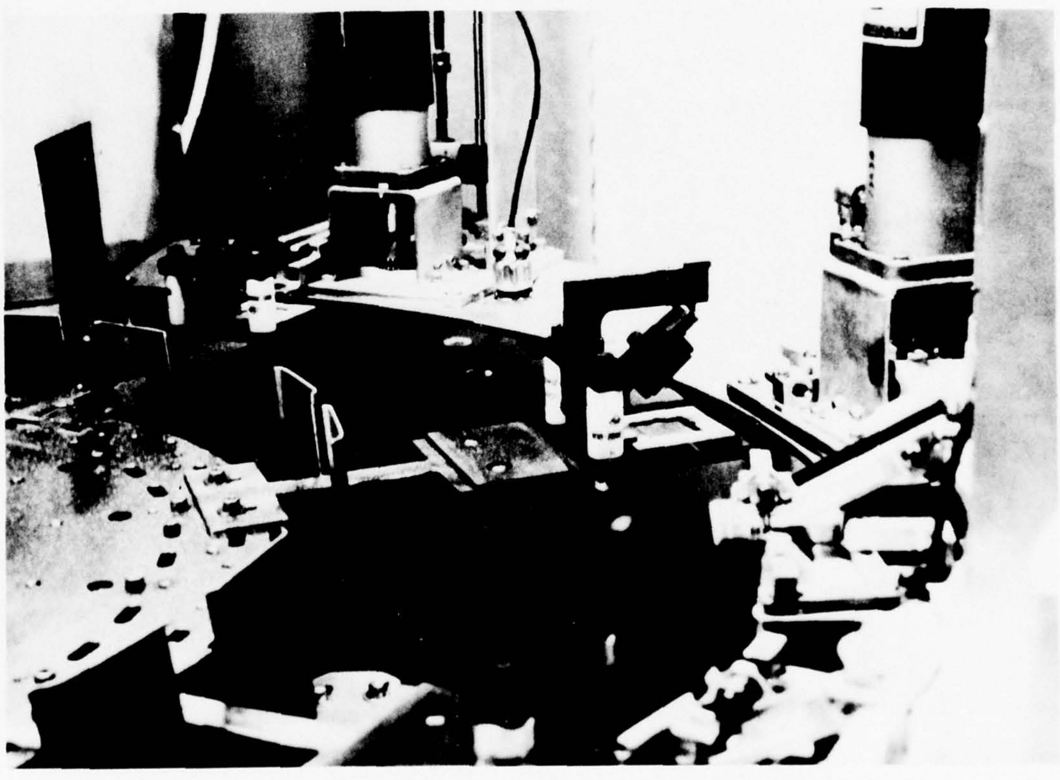


Figure 10b. Pallet Assembly

TABLE 1

DESCRIPTION OF PROCESS TABLE STATIONS

STATION NO.	OPERATION	DESCRIPTION
1	Load Solar Cells	Cells are guided into position in alignment jig of graphite pallet.
2	Load Glass Covers	Covers are guided into position in alignment jig of graphite pallet.
3	Inspect and Adjust	
4	Lower Contact Arm	Spring loaded arm on pallet applies pressure and electrical contact to cover.
5	Oven Pre-heat	Graphite pallet enters oven and is heated to the bonding temperature.
6	"	"
7	"	"
8	High Voltage Bonding	High voltage is applied to the contact arm to make the ESB bond.
9	"	"
10	"	"
11	Pallet Cool-down	Pallet enters cooled zone of the oven
12	"	"
13	"	"
14	Lift Contact Arm	Spring loaded arm on pallet is raised and locked in "up" position.
15	Inspect for Unbonded Areas	
16	Unloaded Bonded Cells	Bonded solar cells are transported from process table to electrical inspection station.

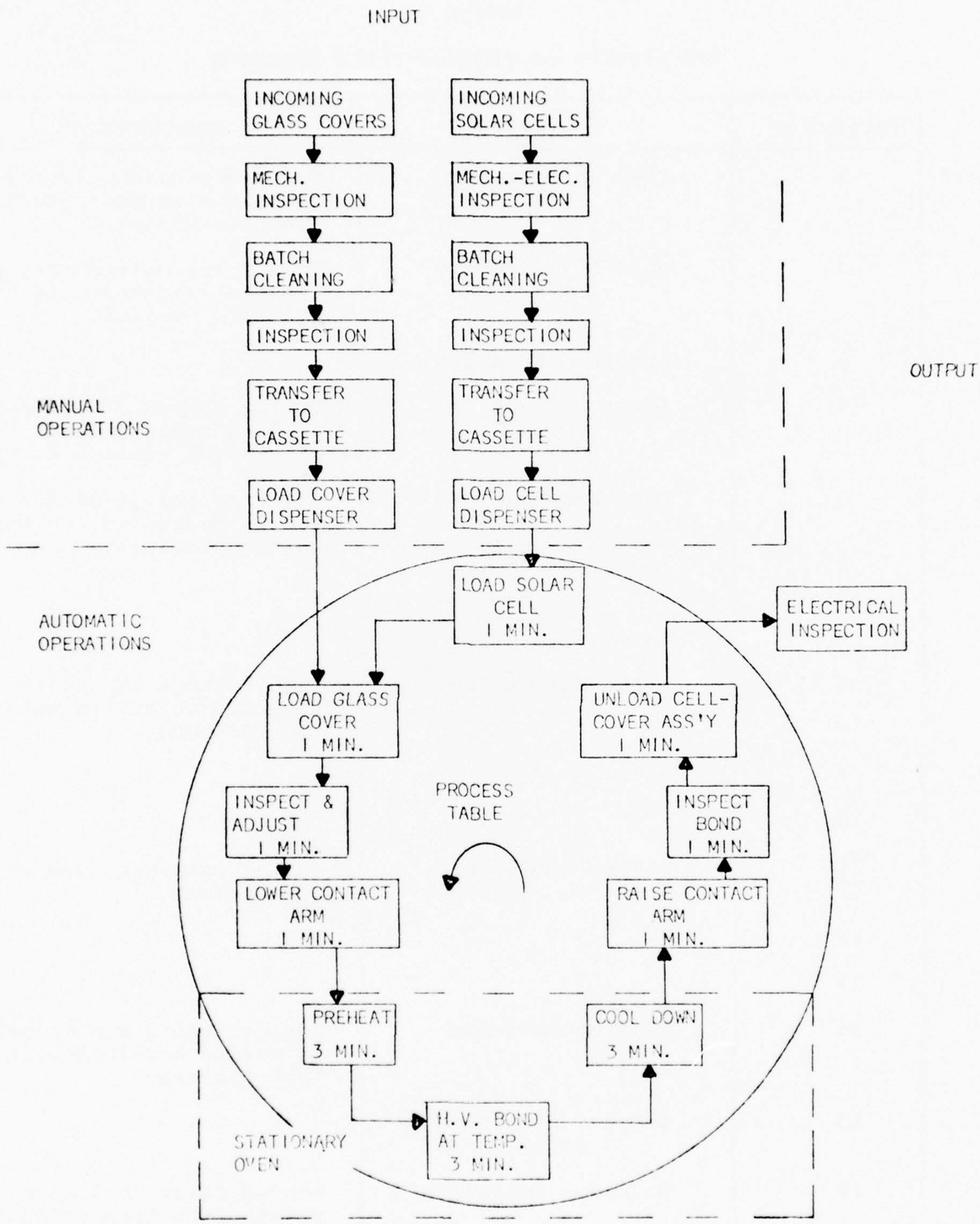


Figure 11. Schematic Block Diagram of Pilot Production Bonder Process

position in the alignment jig. At the next station an optional inspection can be made through a stereo microscope. Normally this inspection is not necessary but under some circumstances such as during grooved cover bonding it may become desirable to insure proper cell-cover positioning. At the next station a spring loaded contact arm holding the top electrode is slowly lowered onto the loaded cell and cover. The pallet then moves into an enclosed oven for the next nine steps including three preheating stations, three stations at processing temperature while voltage is applied and three cooling zone positions. Figure 12 shows experimental temperature profiles during one representative set of processing conditions. Upon exiting from the oven, the contact arm is raised and locked open at station 14. An inspection of the now integrally covered cell can be made at the next station and finally at the last position the covered cell is automatically unloaded from the alignment jig and transferred to an exit cassette for completed cells.

The bonder can complete 60 cells per hour with a maximum of 16 cells in process at any given time. The unit can be programmed such that cells and covers will be dispensed only onto any number of specifically selected pallets to allow reduced rates still under automatic operation to less than 4 cells per hour. For the development program only four processing pallets were constructed and utilized for an available maximum of 15 cells per hour. The bonder can be switched to manual operation for developmental use and each process can then be separately controlled and operated. The bonder provides ability to run up to 4 separate bonding voltage conditions concurrently with any particular pallet receiving whichever process voltage is selected for it. This capability is for development studies on the effects of process parameter variations.

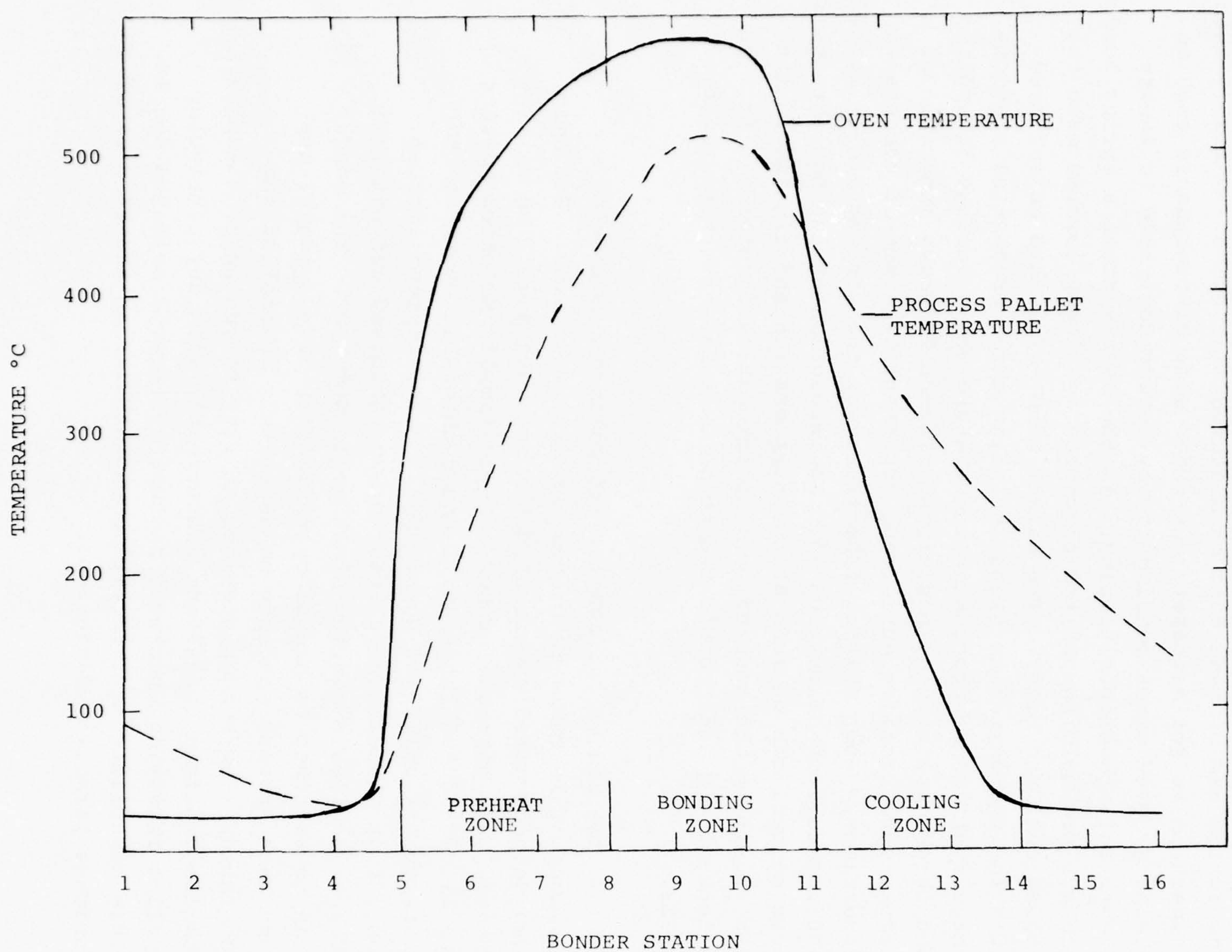


Figure 12. Temperature Profiles of Automated Bonder During Typical Operation

Problems encountered in the operation of this bonder, which are related to the electrostatic bonding process per se are discussed in Section 3.3.6. Other problems involving the facility itself included mainly difficulties with cells and glass slides in the alignment jigs and some deterioration of the processing pallets.

The jigs were made of machinable ceramic with rather tight spacings and tolerances to insure precise orientation of cells and covers. However dimensions of sample cells and particularly of covers used in the developmental work tended to vary somewhat. Due to the tight jigs and variability of piece dimensions, bonding failure sometimes occurred because the cell or cover did not seat properly in the jig. Solution for the problem requires that the jigs be very carefully prepared and that specified tolerances be held on dimensions of cells and covers. Table 2 specifies characteristics of cells compatible with the automated bonder as presently equipped. Cells with other characteristics, for example different size, could be handled by changing fixtures of the bonder.

Many of the components of the processing pallets and some of the high voltage elements within the bonder oven were initially fabricated of high density graphite. This selection was based upon several factors related to consideration of the cyclic high temperature environment and materials'best suited for it. Experience has shown the choice of graphite to be an error. After applications of covers to several hundred cells using this bonder facility, graphite components exhibited considerable erosion, increase of porosity and loss of mechanical strength. The problem is one of several which occurred because oxygen was not adequately excluded from the high temperature zones of the oven. After completion of the experimental work of the program the graphite components were replaced by redesigned items of stainless steel. Better oxygen exclusion must still be added.

TABLE 2

SPECIFICATION SHEET

SILICON SOLAR CELLS FOR ESB COVERS

1.0 SCOPE

This specification defines parameters of silicon solar cells compatible with electrostatically bonded integral covers and consistent with the capabilities of the automated bonder facility as presently operated and fixtured.

2.0 REQUIREMENTS

2.1 Materials

2.1.1 Silicon - Boron doped, single crystal P-type with resistivity between 0.5 and 15 ohm-cm.

2.1.2 Contacts - Evaporated titanium overcoated either with evaporated silver or with evaporated palladium in turn overcoated with evaporated silver.

2.1.3 Anti-Reflection Coating - Silicon monoxide (SiO_x) or ditantalum pentoxide (Ta_2O_5).

2.2 Configuration

2.2.1 Dimensions - 0.787" (±0.003) x 0.787" (±0.003) x 0.010" (±0.002).

2.2.2 Surface Finish - Polished or acid bright etched without saw marks

2.2.3 Cell Wafer Profile - Wafer top surface shall not be rounded near its edges.

2.2.4 Junction Depth - 0.1 to 0.3 μm

2.2.5 Front contact - The front contact will consist of a single rectangular bar along one edge and either (i), not more than 8 equally spaced parallel grid lines perpendicular to the bar, with grid thickness not more than 3 μm, or (ii), not more than 20 equally spaced parallel grid lines perpendicular to the bar with grid thickness not more than 10 μm.

TABLE 2 (Continued)

2.2.6 Solder - Cell contacts shall not have solder coating prior to bonding.

2.2.7 Stray Metallization - Cell active surface shall not contain any areas of contact metallization except in the defined pattern of 2.2.5.

2. SURFACE REQUIREMENT TESTS

A starting point for experimental bonding investigations was a simple examination of quality and cleanliness required on the surfaces to be bonded. Starting with polished slides of 7070 glass and flat polished silicon wafers, tests were conducted to determine how much the glass surface could be degraded before good bonding could no longer be achieved. Variations in surface quality on the glass were made by mechanical lapping. Standard bonding parameters for the tests were 1200 volts for three minutes at 450°C after approximately one minute of preheating. Results were as follows:

Glass Surface	Silicon Surface	Bond
Polished	Polished	Excellent
Lapped with 0.05 μm grit	Polished	Excellent
Lapped with 0.25 μm grit	Polished	Excellent
Lapped with 0.3 μm grit	Polished	Excellent
Lapped with 1 μm grit	Polished	Excellent
Lapped with 3 μm grit	Polished	Poor
Lapped with 5 μm grit	Polished	None

Bonds were then attempted between polished 7070 glass slides and silicon wafers with surfaces lapped with 5 μm grit and with the same silicon after removal of approximately 75 μm of material with a 6-1-1 etch. Results in this case were:

Glass Surface	Silicon Surface	Bond
Polished	Lapped with 5 μm grit	None
Polished	Lapped with 5 μm grit then 6-1-1 etched	Excellent

It may eventually be possible to obtain 7070 glass in thin sheet form directly from a process such as that used by Corning to produce type 0211 Microsheet product. To confirm acceptability of this surface quality, bonds were made between 0211 Microsheet slides and polished silicon and lapped then etched silicon. Evaluations had to be made at process temperature because expansion coefficient mismatch caused catastrophic failure of samples reaching room temperature as was shown in Figure 1. It might be pointed out that the bonds did not fail. Results were as follows:

Glass Surface	Silicon Surface	Bond
Microsheet	Polished	Excellent
Microsheet	Lapped with 5 μm grit then 6-1-1 etched	Excellent

Samples for all the tests above were cleaned in an ultrasonic bath of trichlorethylene and then blown dry with nitrogen. To check on the degree of cleanliness required, bonds were attempted between polished glass and polished silicon surfaces with one surface intentionally contaminated by finger prints or residual traces of talcum powder dust from a finger cot. Tests were repeated with intentionally contaminated surfaces subsequently cleaned with trichlorethylene using a cotton swab and then an ultrasonic bath. Results of these tests were:

Glass Surface	Silicon Surface	Bond
Polished	Polished but contaminated by finger print	Good with cosmetic flaw
Polished	Polished but contaminated by talcum dust	Good except at location of dust particles
Polished but contaminated by finger prints	Polished	Good with cosmetic flaw
Polished but contaminated by talcum dust	Polished	Good except at location of dust particles
Polished and cleaned after contamination	Polished and cleaned after contamination	Excellent

From all of the tests discussed, several conclusions could be drawn. The standard surfaces on cells and cover glasses are more than adequate for ESB cover purposes. The surfaces of a microsheet form of 7070 would not need additional preparation. Routine cleaning procedures are satisfactory for ESB processing.

3. SOLAR CELL EXPERIENCE

Initial experiemntal work with ESB covers on solar cells involve some elementary, yet critically important, investigations. Basic process parameters had to be determined for producing flaw-free bonds over areas at least as large as the solar cell. Demonstration had to be made that the ESB cover could be applied to a functioning solar cell and would not inherently alter performance of the solar cell junction. Once these starting points had been established, a major part of the program involved development of capability for applying ESB covers to solar cells of several types to identify prospects and limitations of the method. Summarized in the sections below are the results of experience with each cell type.

(a) OCLI Standard N/P Cells

The solar cell structure most emphasized under the development program was one more or less representative of present production cells for spacecraft: 2 x 2 cm, nominal 250 μm thickness, 10 Ω-cm N/P. Optical Coating Laboratory, Inc. supplied a number of variations of this standard cell. All of these cells had polished front surfaces, six finger contact grids and approximately 0.3 μm deep diffused junctions. Procedures were successfully developed for applying grooved and plastically deformed covers, usually 250 or 300 μm thick, to OCLI cells with the following contacts and antireflection coating materials:

Contacts:	Titanium-silver
	Titanium-palladium-silver
AR Coatings:	SiO_x
	Ta_2O_5

As with glued covers, performance limitation of integrally covered cells relative to that before covering was determined by the antireflective coating material. Figure 13 shows before and after I-V characteristic behavior for a typical cell with SiO_x coating. Observed short circuit current loss of approximately 3%. due to covering is expected for the nonoptimized n ≈ 1.9 AR coating. Figure 14 illustrates an example of a cell with high refractive index Ta_2O_5 coating which showed current gain as expected after cover application.

Some variability of the optimization of the Ta_2O_5 coating apparently involving control of refractive index was observed between cells from different OCLI groups. Figure 15 illustrates the results of a test to compare average changes in cell short circuit current and maximum power after covering a few cells of four different types with integral 7070, glued 7070 and glued 7940 fused silica covers. Adhesive for the glued covers was Dow Corning

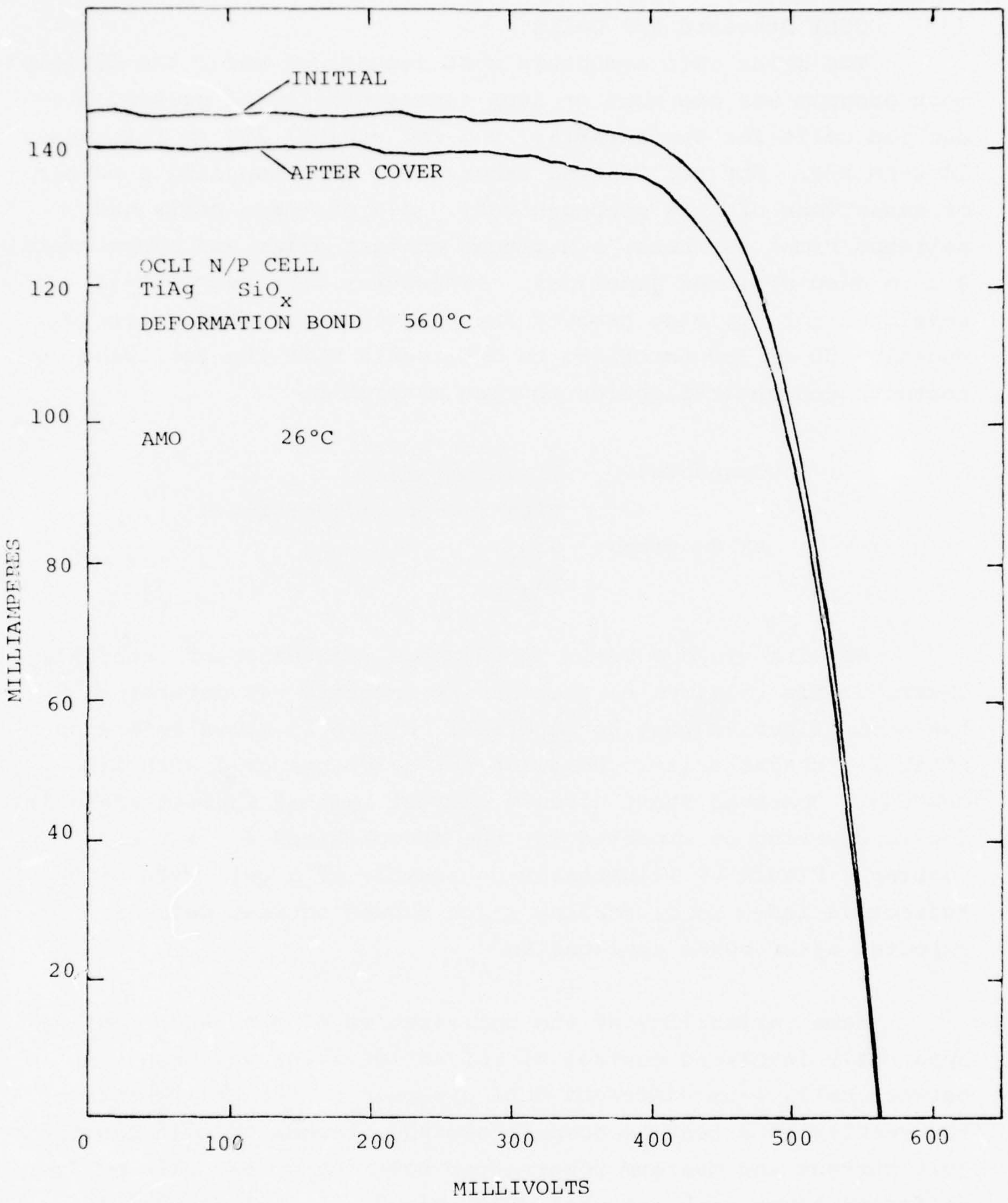


Figure 13. AMO I-V Characteristics of OCLI Cell With SiO_x Coating Before and After ESB Cover

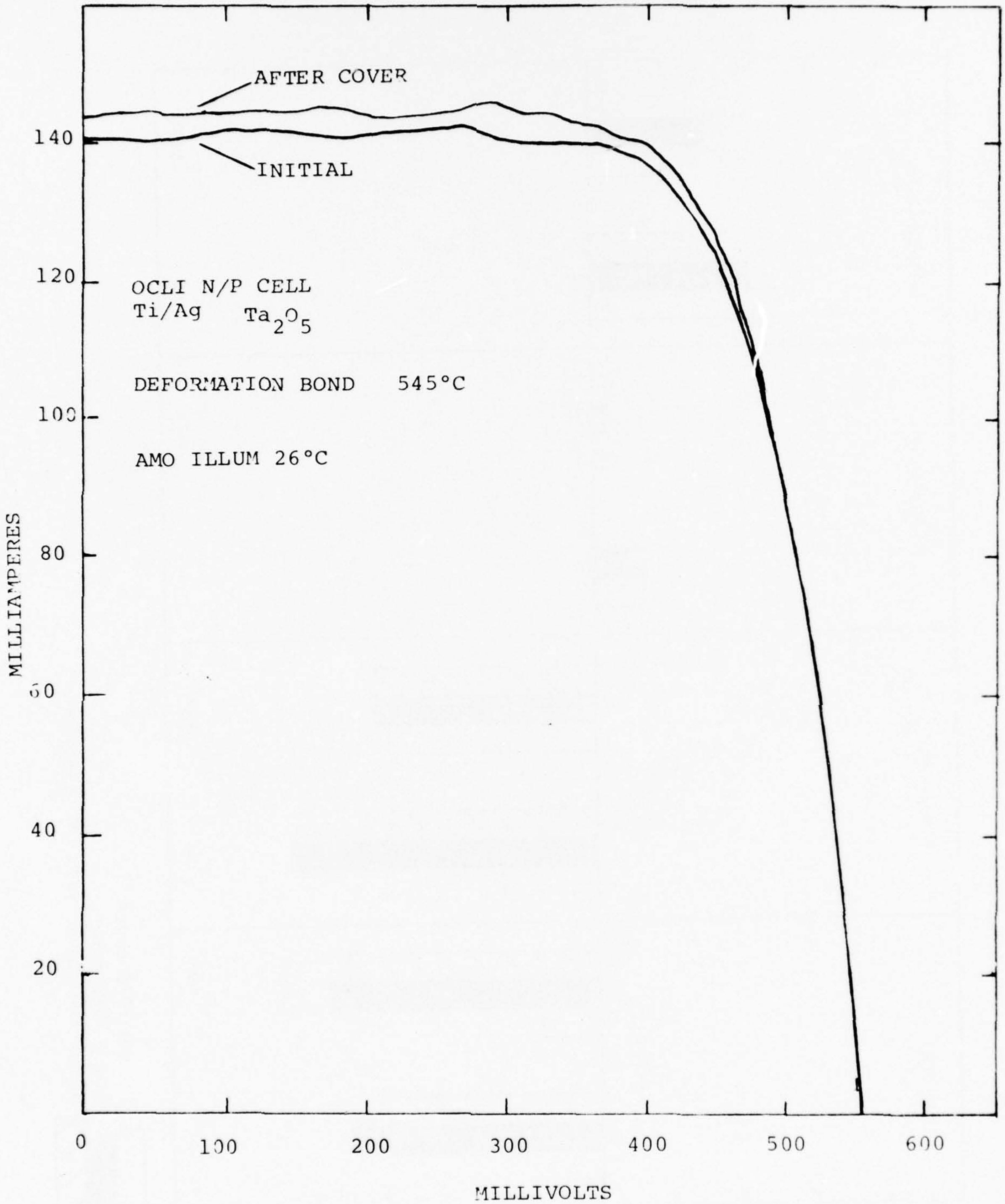


Figure 14. AMO I-V Characteristics of OCLI Cell With Ta_2O_5 Coating Before and After ESB Cover

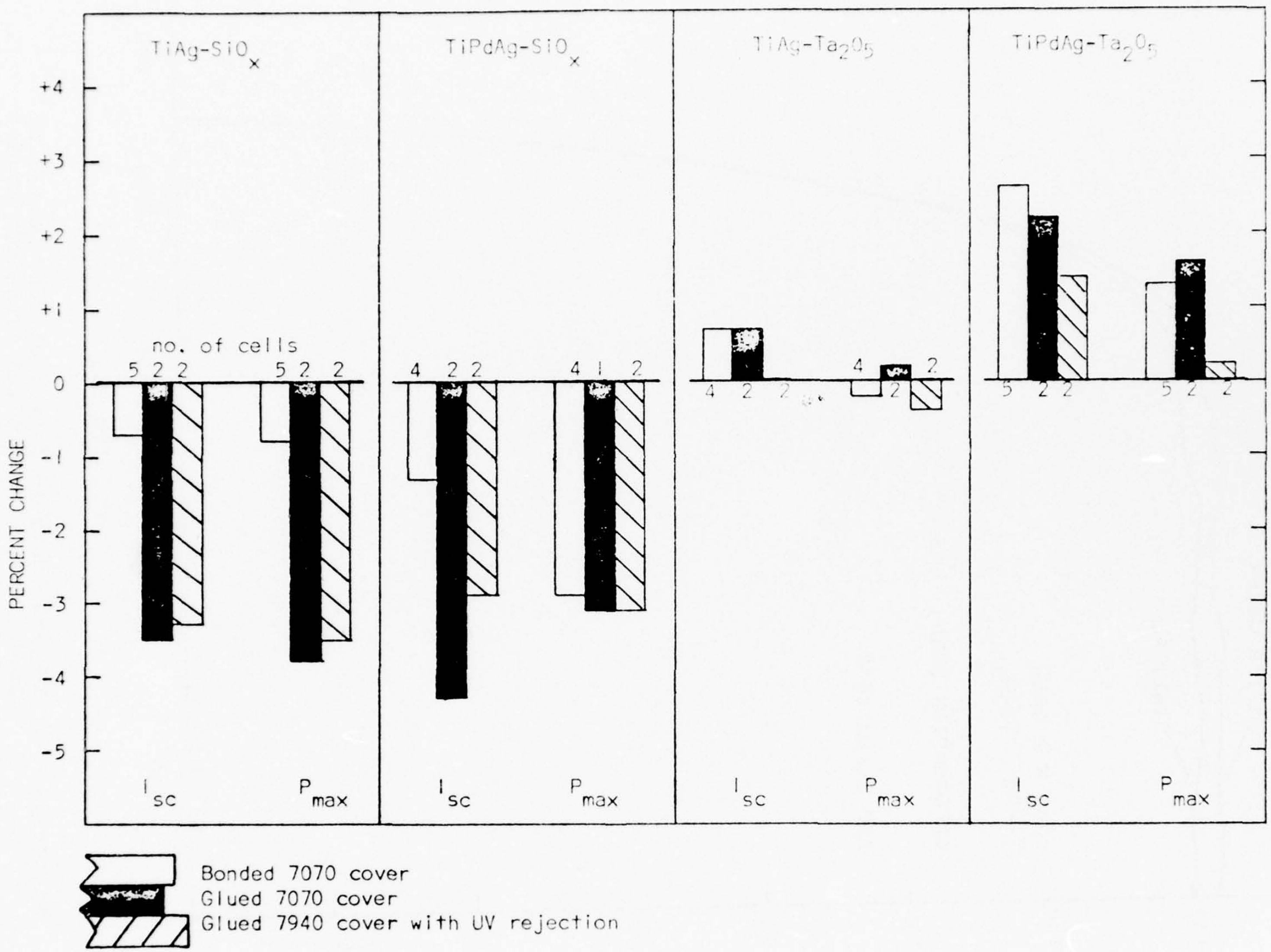


Figure 15. I_{sc} and P_{max} Changes Due to Cover Applications

Sylgard 182. The fused silica covers had 400 nm cut on UV filters. It is evident that the AR coatings of the TiAg - Ta_2O_5 cell group were inferior to those of the TiPdAg - Ta_2O_5 group. It is also interesting to note that among the cells with SiO_x coatings, those receiving integral 7070 covers showed smaller I_{sc} and P_{max} losses than those with either the 7070 or 7940 glued covers. With the Ta_2O_5 AR coatings the integral and glued 7070 cover results were comparable and measurably better than those with the filtered 7940 covers.

Not all integrally covered cells showed acceptable performance after the ESB process. Among the titanium-silver or titanium-palladium-silver contacted OCLI N/P cells, two characteristic types of performance deterioration were found to occur. Figure 16 shows I-V characteristics typical of a cell which experienced significant increase in series resistance due to the covering process. At the time it was not recognized that this is an oxidation problem at the titanium layer of the contacts due to oxygen penetration through the silver. This will be discussed in Section 3.3.6. Some cell lots were much more susceptible to the effect than others and initial reaction was that the correction might be made in the cell processing. Usually a cell exhibiting this problem could be electrically restored as in Figure 17 by exposing it to hydrofluoric acid vapor for about five seconds and then flushing with water. This is not an acceptable "fix" because long term reliability of a contact treated in this manner is very questionable. The second type of electrical degradation likely to occur due to application of ESB covers involved an increase in junction generation-recombination current and loss of cell open circuit voltage apparently due to interaction of the cell front contact with the junction during the high temperature cycle for bonding. This effect is illustrated by the I-V characteristic behavior shown in Figure 18. Again some cell lots were more likely to exhibit this problem than others and generally when it was observed, a small decrease in bonding temperature could avoid the effect in remaining cells from the same group.

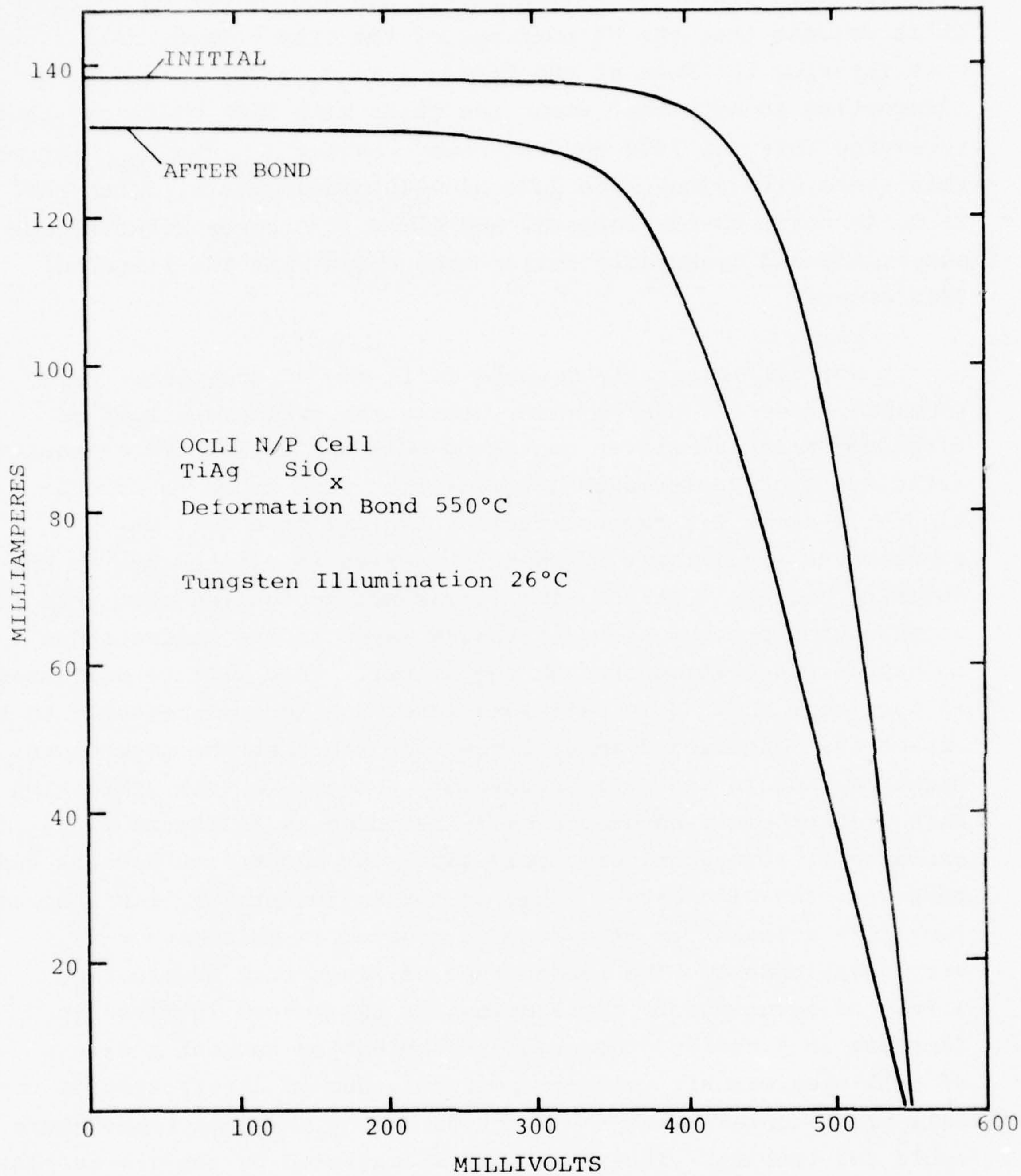


Figure 16. I-V Characteristics of Cell with Series Resistance Problem After Bonding

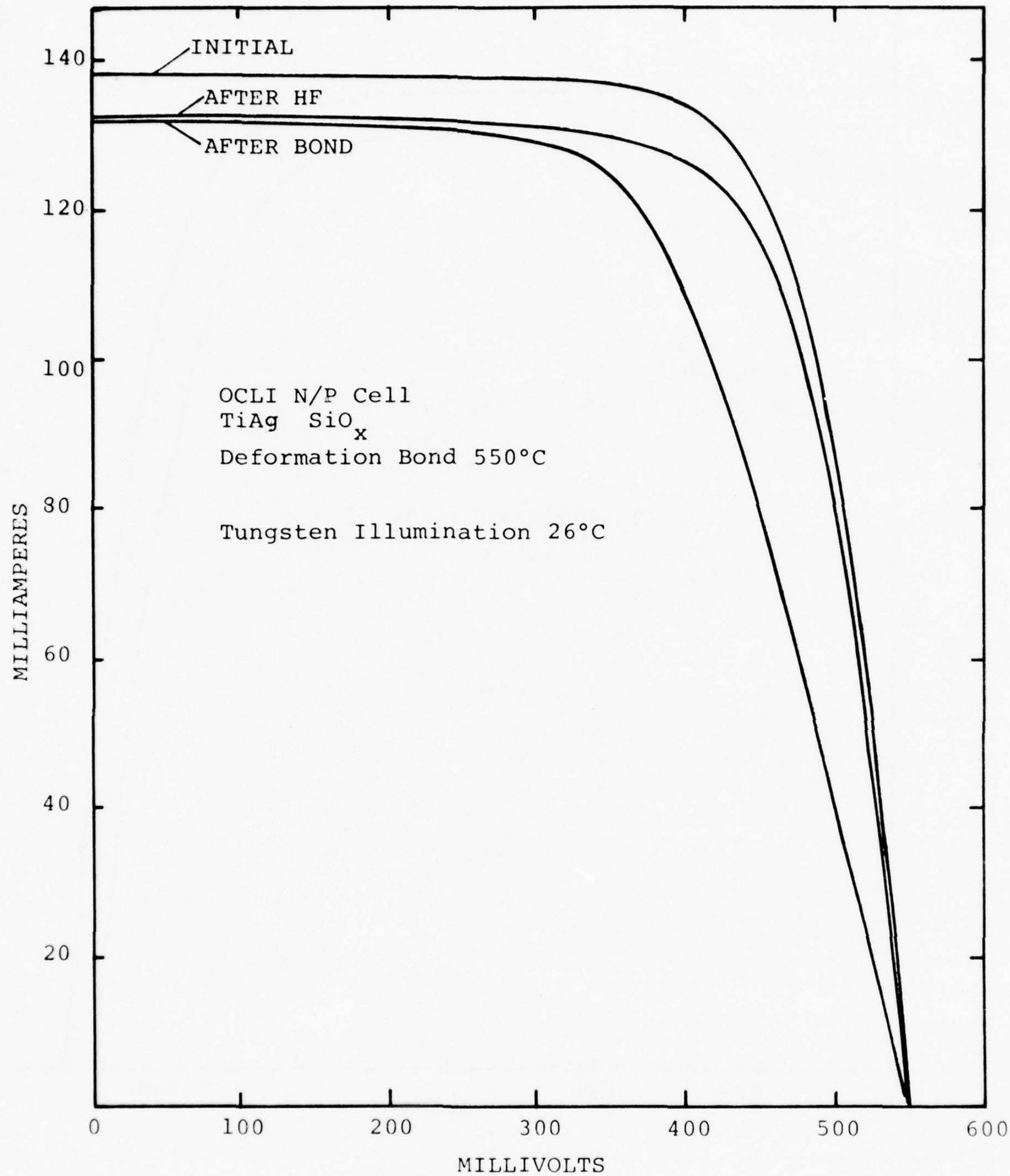


Figure 17. The Effect of HF Exposure on Covered Cell with Series Resistance Problem

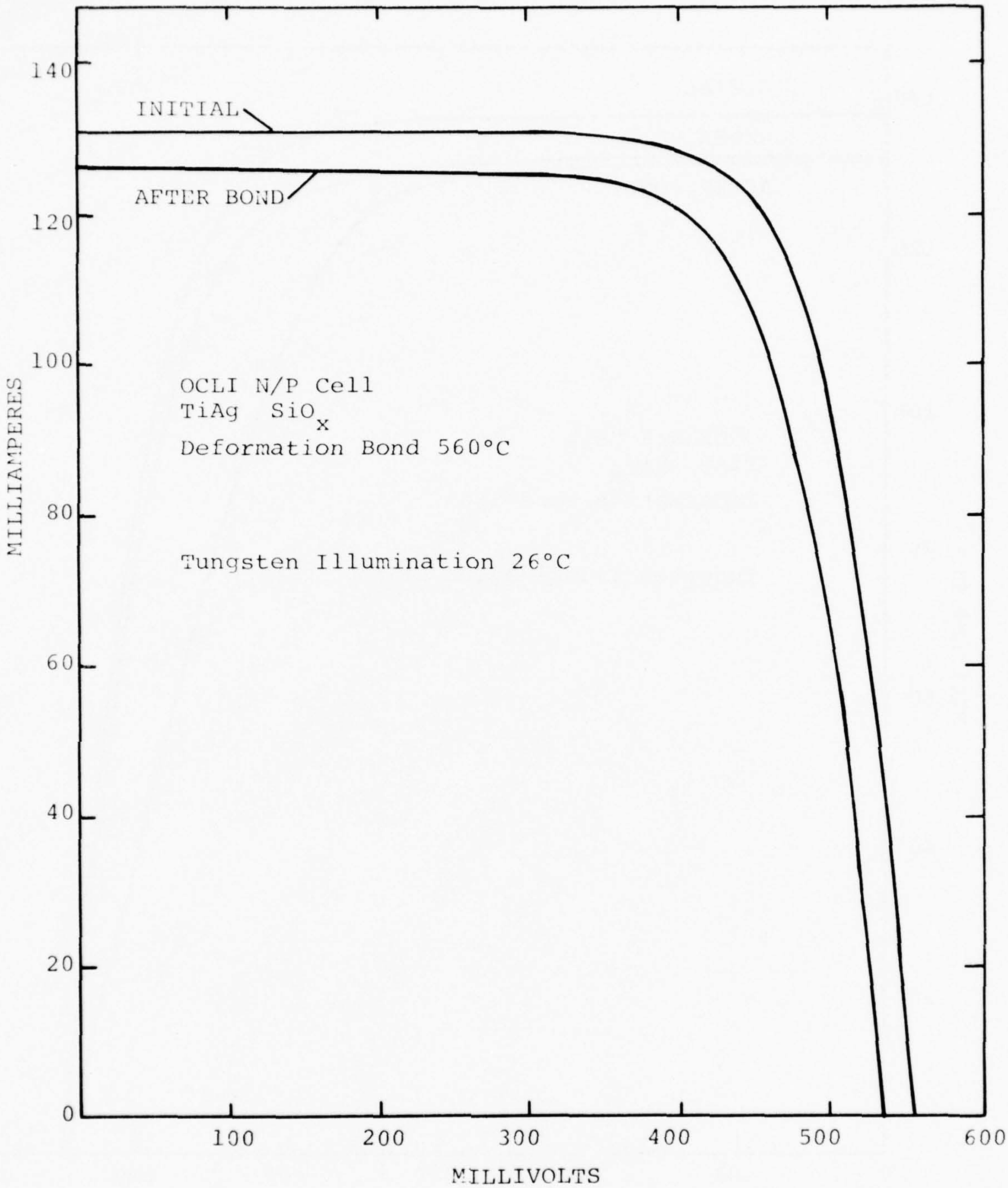


Figure 18. I-V Characteristics of Cell Exhibiting V_{oc} Loss After Covering

To achieve mechanically and cosmetically acceptable integral covers by plastic deformation of the 7070 glass while using a maximum temperature of approximately 560°C for three minutes, it was found that the front contact grid thickness on the cell should not exceed roughly 3 μm. Adequate thickness for the titanium-silver contact on a standard 2 x 2 cm cell is in the range of 2 to 3 μm so that control of cell contact thickness and uniformity was required to be considerably better than is present production practice. Even with controlled metal thickness, problems were encountered in trying to apply deformation type covers to cells with more than 4 or 5 grid lines per cm. Grooved covers allowed bonding to be performed at temperatures below 500°C for cells with virtually any cell grid pattern thickness providing the pattern was systematic and the active surface of the cell did not include stray metallization.

(b) Spectrolab N/P Cells

The original plan for this program did not involve consideration of solar cells from more than one manufacturer. However because of generally successful developmental results in applying ESB covers to OCLI cells, it was decided, toward the end of the program, to also evaluate Spectrolab N/P cells.

For ESB cover application, the typical Spectrolab N/P cell has several significant dissimilarities from equivalent OCLI cells. Among the differences are:

(i) The silicon front surface is chemically etched on the Spectrolab cell as opposed to polished on the OCLI cell.

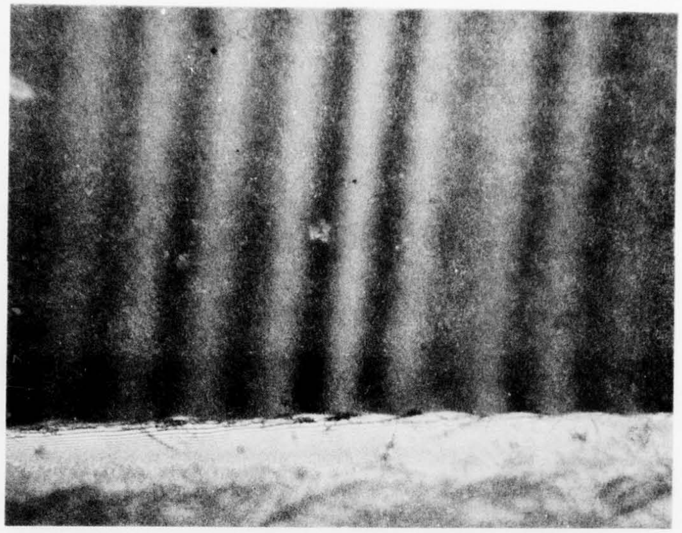
(ii) The Spectrolab cell has "pillowed" rather than essentially square edges.

(iii) Spectrolab cells exhibit different performance stability at high temperatures.

These characteristics have little importance for glued covers and are not usually considered under standard production specifications. But for ESB integral covers the differences are substantial.

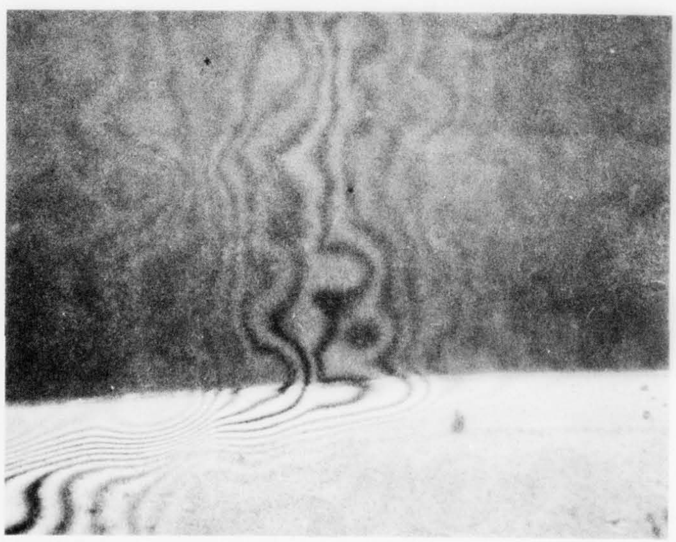
Figure 19 shows interference fringe micrographs of typical surfaces on OCLI and Spectrolab cells to illustrate the relative microscopic surface structure of polished and bright etched silicon respectively. Good electrostatic bonds can be formed on etched surfaces. Because at least microscopic deformation of the glass to conform to the surface must take place, minimum bonding temperature used for the etched surface was approximately 480°C compared to 450°C for a smooth polished surface. Figure 20 shows a microscopic view of the electrostatic bond on an etched surface. Macroscopically the bond appears uniform and cosmetically acceptable. Mechanically the electrostatic bond to etched silicon is stable and fully adequate. A problem could have resulted if coarse features remained from heavy saw marks. In general the Spectrolab cell etched surface presented no difficulty for the ESB process.

The standard etching process for the Spectrolab cell results in a slightly rounded or "pillowed" wafer edge. Typical samples, used in this program had top surfaces which rolled 20 to 50 micrometers away from flat in the vicinity of the edges. A plane glass slide when bonded to the pillowed edge cell could not deform sufficiently so as to bond all the way to the cell edge. As a result the slide was left cantilevered and unattached along three edges of the cell as illustrated in the sketch of Figure 21. Width of the unbonded frame depended upon the particular cell and process conditions but could usually be reduced to less than 0.030 inch. The effect of the unattached cover along the cell edge is apparently cosmetic and relatively unimportant except that fairly careful handling is necessary to insure that the overhanging glass edge does not chip to leave an exposed region on the active surface of the cell.



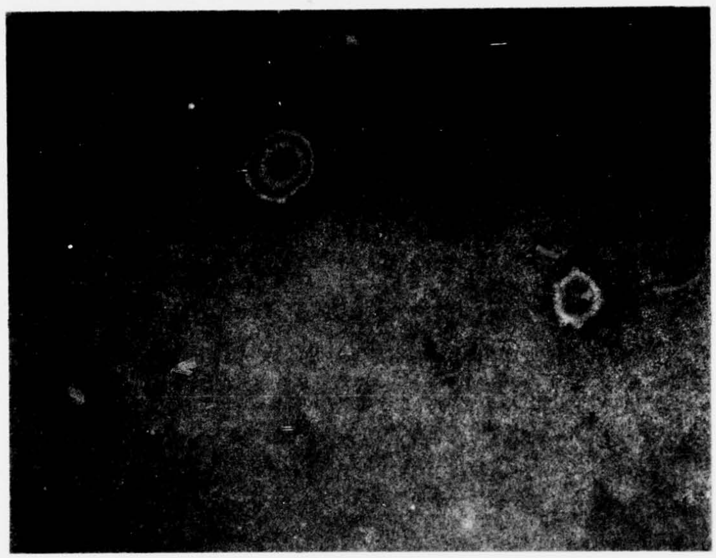
320 X

Figure 19a. Interference Fringes on OCLI Polished Surface Cell



320 X

Figure 19b. Interference Fringes on Spectrolab Etched Surface Cell



200 X

Figure 20. Microscopic Unbonded Areas Under ESB Covers on Etched Surface Cell

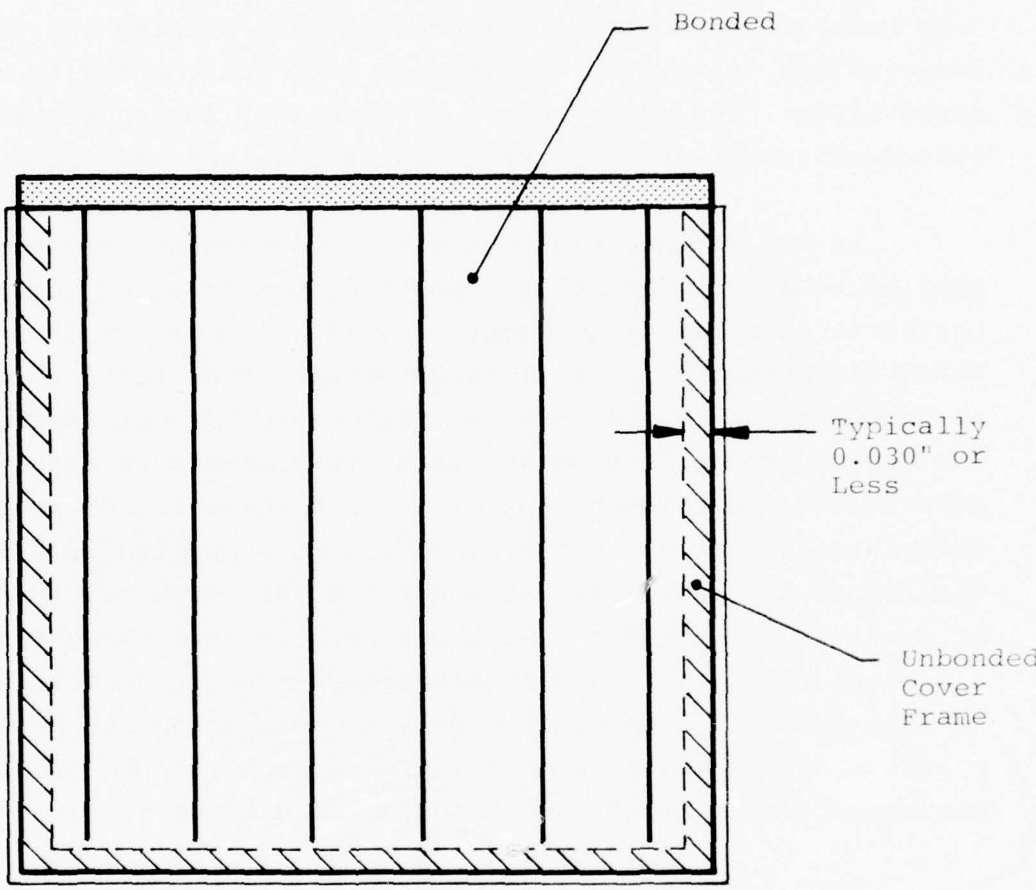


Figure 21. Configuration of ESB Integral Cover on Spectrolab Pillowed Edge Cell

In order that a decision regarding acceptability of an unbonded ESB cover around the edges of a pillowed edge cell would not have to be made, Spectrolab provided modified process cells with square edges for integral cover purposes. These cells continued to have etched surfaces but the etching was done on large wafers from which cell blanks were later cut with a high speed blade. The method would be practical for production. All subsequent work with Spectrolab cells involved sawn edge cells.

It was assumed that plastically deformed covers would be applied to Spectrolab cells. Spectrolab maintained metallization thickness on a six finger contact grid at a maximum of not over three micrometers. Initial experimental cover tests showed that at temperatures between 535 and 560°C used for deformation bonding, the Spectrolab cells with standard titanium-silver contacts experienced significant loss of V_{oc} and curve factor as in the example of Figure 22. Grooved covers were applied to a few samples of the same cells at 500°C and less with only minor loss of cell output. At the time, these results were thought to indicate a need to alter the standard Spectrolab contact process in order to make the cell compatible with the deformation ESB cover. Recent reconsideration suggests that better control of the bonding process environment might have been an adequate correction.

Tests were conducted on cells with unsintered titanium-silver contacts to determine feasibility of combining the ESB cover application and sintering processes. As in the example of Figure 23, resulting covered cells showed electrical performance improvement due to the combined cover bonding/sintering operation at approximately 560°C for three minutes. Use of the unsintered contact was selected for a quantity of Spectrolab cells to be covered in the pilot production bonder as deliverable items under this program.

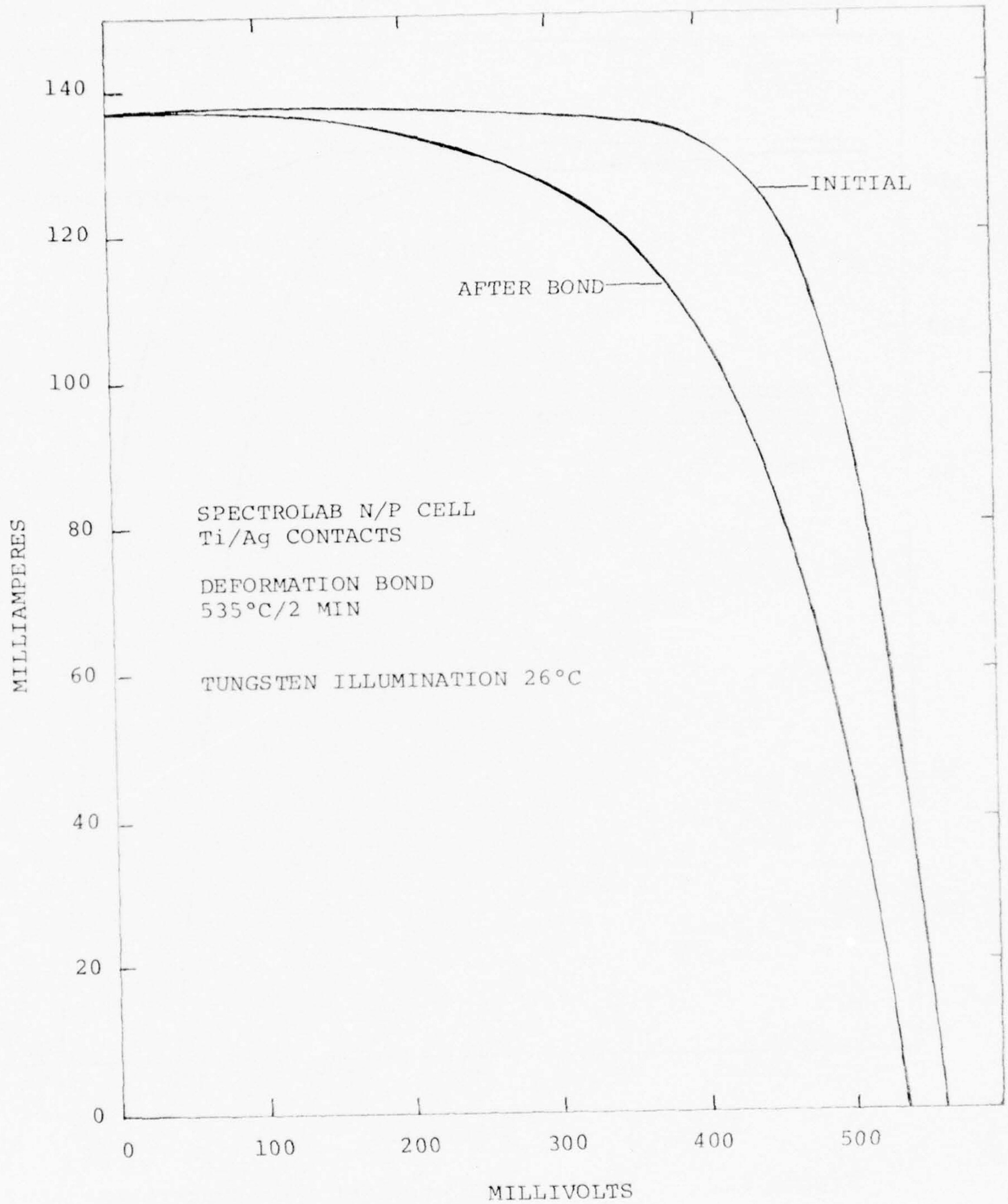


Figure 22. I-V Characteristics for Spectrolab Cell With Deformation Bond Cover

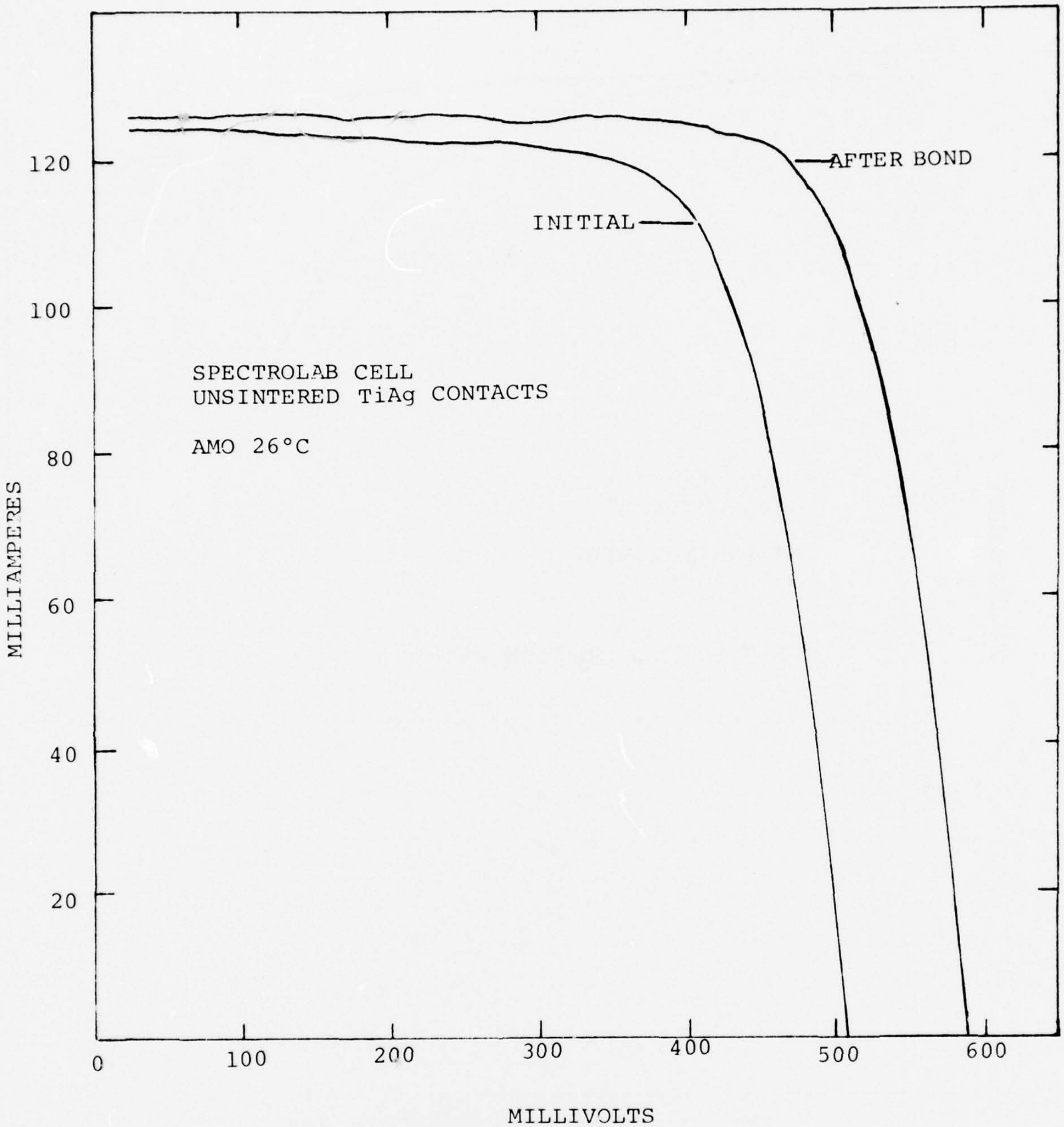


Figure 23. AMO I-V Characteristics of Spectrolab Cell With Unsintered Contacts

As will be discussed in Section 3.3.6, the cells with unsintered contacts later showed poor contact adherence after cover bonding in an inadequately controlled atmosphere. Except for the contact problem, cover results on the Spectrolab cells were good. Elimination of the interaction between cell contacts and residual oxygen in the bonder atmosphere would allow the Spectrolab N/P cell without pillowed edges to be fully compatible with plastically deformed or grooved ESB covers.

(c) Simulation Physics N/P Cells

ESB covers have been applied to several types of silicon solar cells fabricated by Simulation Physics. The cell types which were prepared and tested for compatibility with electrostatically bonded 7070 glass covers included:

(i) Ion implanted junction cells.

(ii) Cells with CeO_2 antireflective coatings.

(iii) Aluminum contacted cells.

(iv) Cells with recessed grid contacts.

No problems were encountered in applying covers to cells with ion implanted junctions. Junction depths between 0.15 and 0.30 μm were tested. Behavior was identical to that of similar cells having diffused junctions. Figure 24 shows a typical I-V characteristic from an integrally covered ion implanted cell.

Cerium oxide is a high refractive index ($n \sim 2.3$) anti-reflective coating candidate which might be considered for use on a high efficiency integral cover cell. Sample cells with this

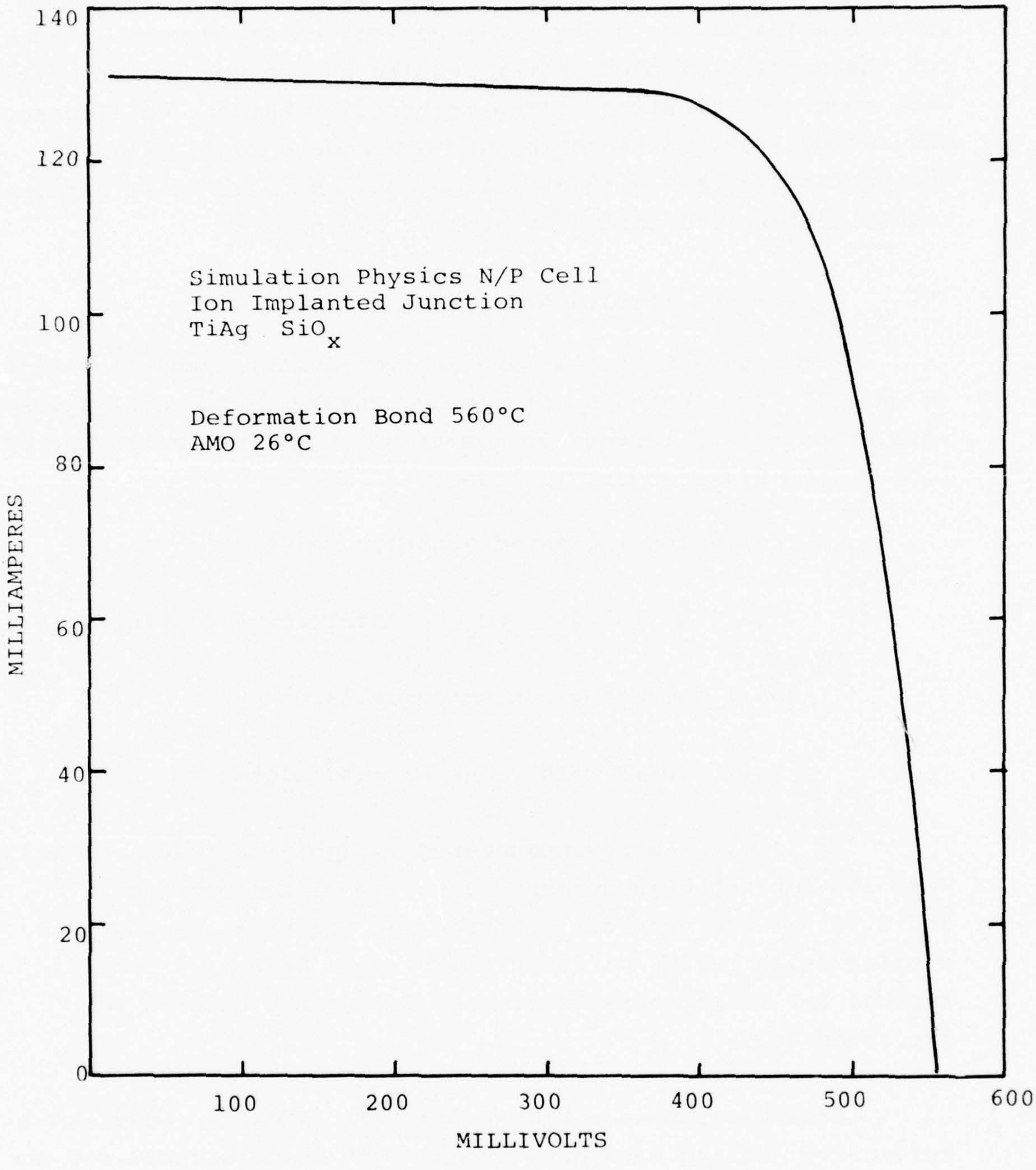


Figure 24. AMO I-V Characteristic of Ion Implanted Cell with ESB cover

AR coating showed AMO output current increase of approximately 3% when glued covers were applied. But 7070 glass covers would not adhere to the CeO_2 coating by electrostatic bonding. After investigation involving a range of bonding parameters it was concluded that CeO_2 is not compatible with electrostatic bonding. The reason probably involves inability of free oxygen ions from the glass to react with the CeO_2 surface.

Cells with all aluminum contacts have been of interest for nuclear hardened arrays. In general, aluminum contacted cells are inferior to cells with titanium silver contacts in their ability to withstand high temperature processes. In order to test the possibility of applying ESB covers to aluminum contact cells, a few diffused junction cells were prepared with aluminum front and back contacts. Two junction depths, 0.2 and 0.5 μm, were used. ESB covers were bonded to the cells at 475°C for three minutes. The 0.5 μm junction depth cells showed no junction degradation but the cells with 0.2 μm junctions exhibited some shunt losses. Representative I-V characteristics are shown in Figures 25a and 25b respectively. It is believed that, if required, modified conditions could be developed to allow ESB covers to be satisfactorily applied to aluminum contacted cells with 0.2 μm junctions.

Most of the ESB cover development involved solar cell types with surface characteristics, grid patterns, junction properties, etc., more or less comparable to what could presently be available in production. Specifications given previously in Table 2 reflect parameters of solar cells shown to be compatible with a particular ESB process and with the existing fixtures of the automated bonder facility. However, a wide variation of these parameters could also be acceptable with appropriate changes in the process and with modifications to the facility.

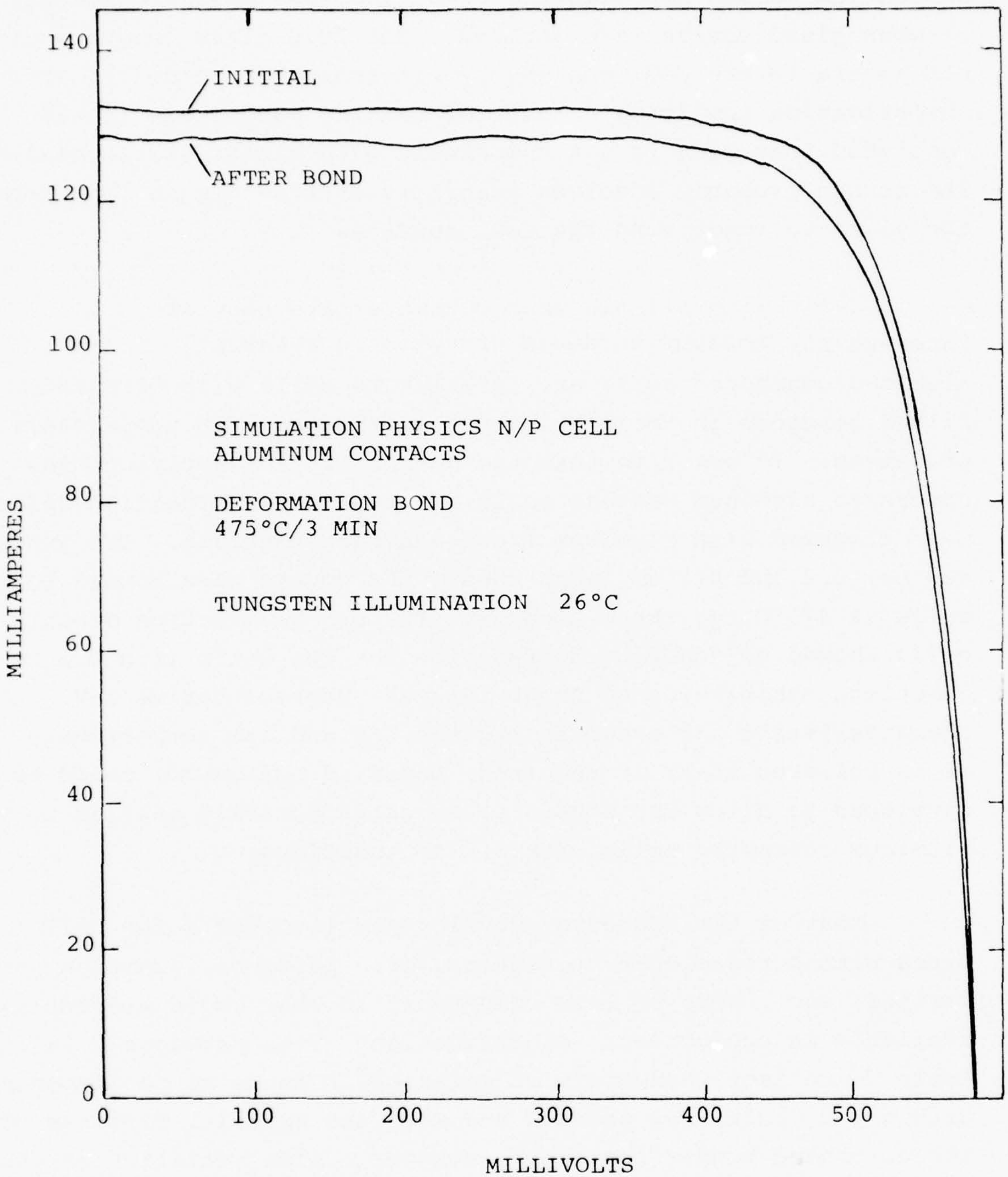


Figure 25a. I-V Characteristics of 0.5 μm Deep Junction Cell With Aluminum Contacts

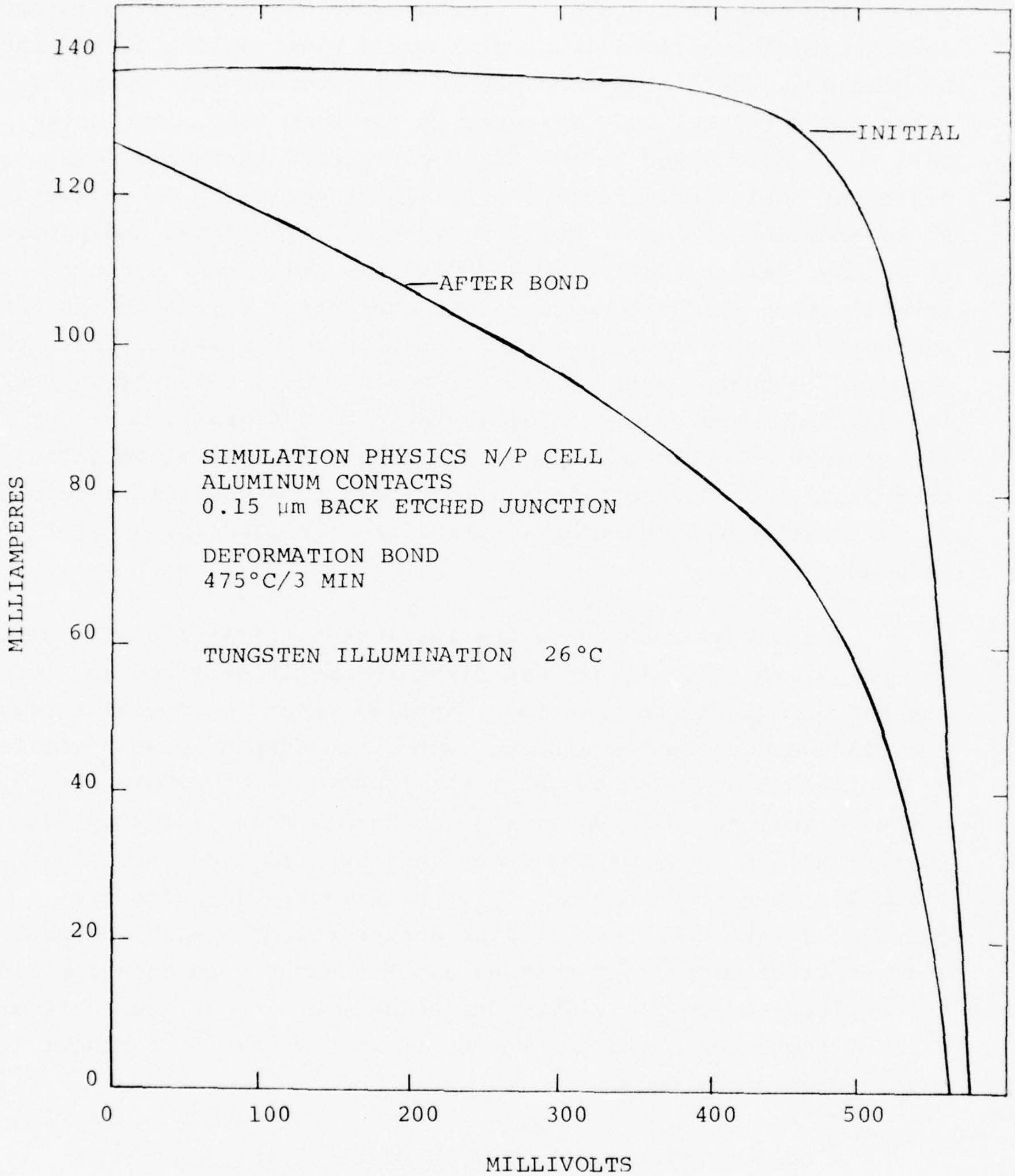


Figure 25b. I-V Characteristics of Shallow 0.15 μm Junction Cell With Aluminum Contacts

The general approach of the program was to develop integral cover application technology which would place as few constraints as possible, preferably none but in practice several, upon the solar cells themselves. However, if for some reason the solar cell could be adapted to the ESB cover rather than vice versa, a different cell configuration would almost certainly be utilized. As an example, the cover could be very easily aligned and applied at process temperature below 450°C if the cell front contact metallization did not project above the active region of the front surface. Samples of such a configuration were prepared under this program. Although impractical for general use, cells of this type, in addition to being exceptionally easy to integrally cover by electrostatic bonding, could be designed with special advantageous characteristics for certain applications. One possibility could be cells with enhanced thermal stability for laser hardness purposes.

A group of such cells was fabricated. Starting with polished P-type wafers, the silicon was first thermally oxidized and then the pattern of the contact to be applied later was opened through the oxide and the silicon below etched to a depth of approximately 5 μm. With the remaining oxide still present, phosphorus was diffused into the exposed silicon to form a deep (~ 0.8 μm) junction just in the vicinity of the front contact grid location. The oxide was then removed and a 0.25 μm implanted junction was introduced into the front surface active region. Back contact, aligned front contact,AR coating and ESB cover were then applied to complete the cell. Figure 26a shows a sketch of the configuration of these cells and Figure 26b is an SEM view of a finger grid region cross section.

A representative cell I-V characteristic is shown in Figure 27. Application of ESB covers onto these cells was easily performed at 450°C. Sample cells with aluminum contacts showed no reduction in shunt resistance when subjected to 450°C for 30 minutes or 500°C for 15 minutes. With a correctly selected contact such cells should have good stability at temperatures to at least 600°C.

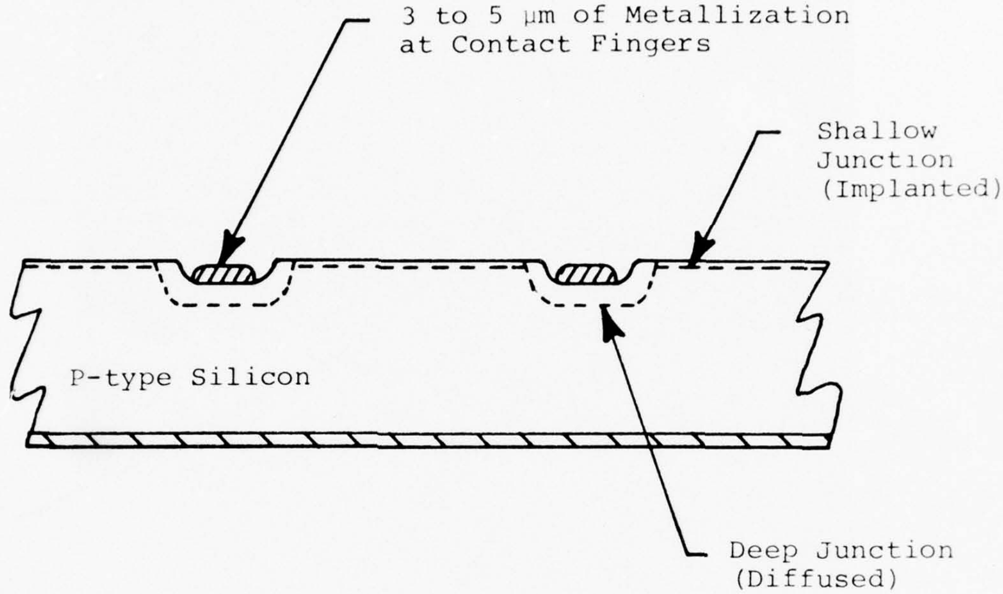


Figure 26a. Recessed Contact Solar Cell Configuration

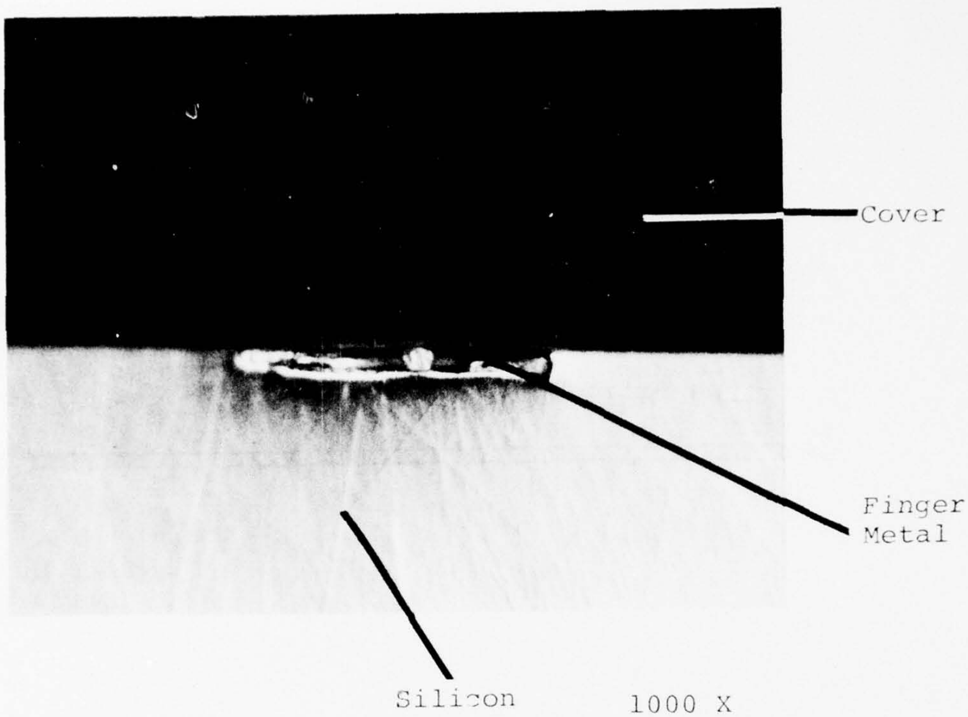


Figure 26b. Edge Section of Finger Region of Recessed Contact Cell

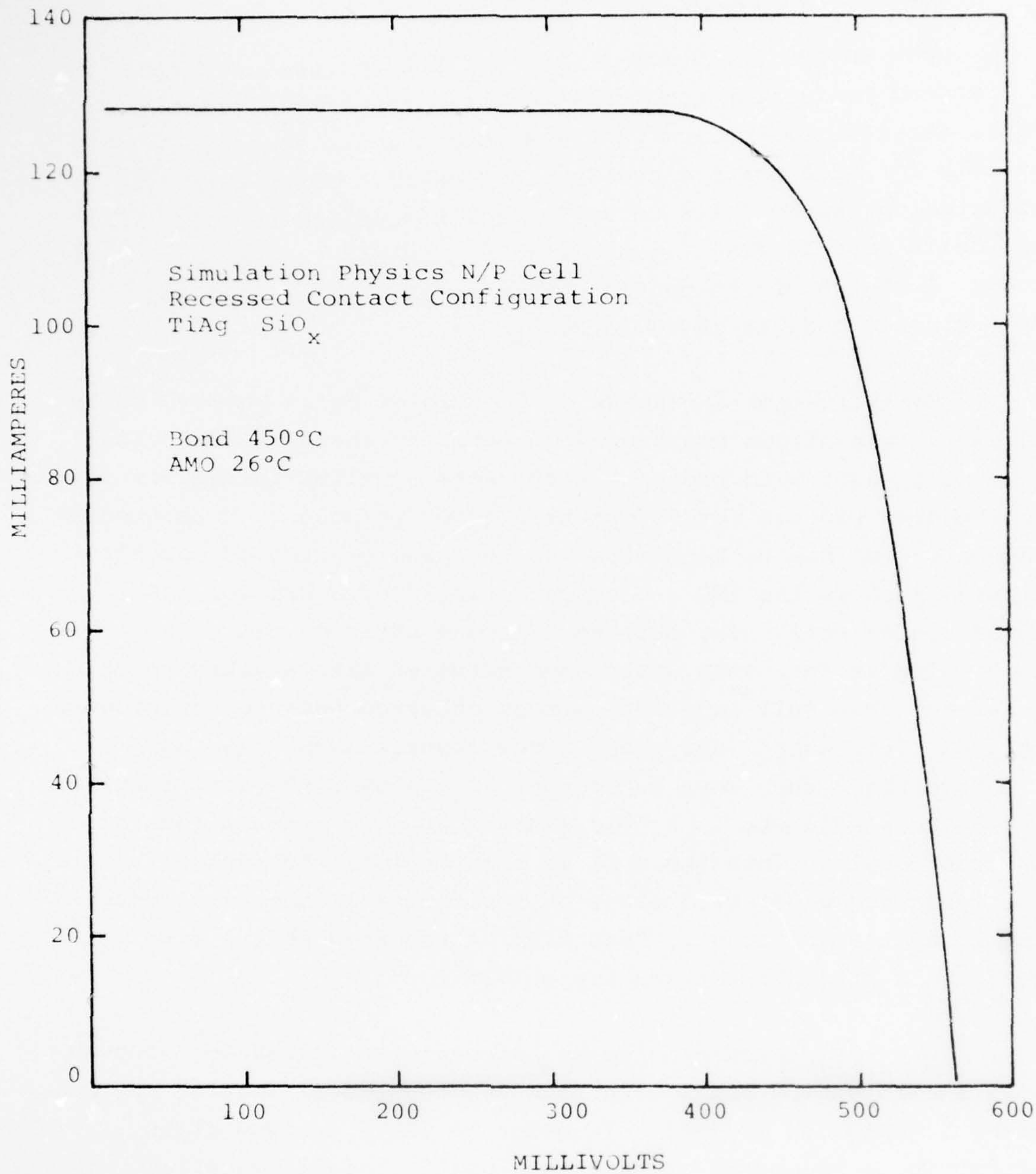


Figure 27. AMO I-V Characteristics of Recessed Contact Cell with ESB Cover

(d) OCLI Violet Cells

Upon successful demonstration of ESB integral covering of standard production type solar cells, it became of considerable interest to confirm that ESB covers would also be feasible for high performance "violet" cells. Tests were conducted on sample 2 x 2 cm violet cells supplied by OCLI. Most cells have 20 fine finger grids orthogonal to two collecting lines. A sketch of the configuration of the cell and of the cover glasses used is shown in Figure 28.

Metallization thickness on the violet cells was typically 10 μm. Glass slides positioned directly on these cells could make no contact with the active surfaces to allow initiation of the bonding process for deformation cover purposes. Consequently demonstration had to be limited to the case of grooved covers. Figure 29 shows the AMO I-V characteristic of a grooved ESB cover violet cell. The current increase after covering is 4 mA which is less than would have resulted with a glued cover. This less than full expected current occurred because the grooves actually introduced into these cover glasses were wider than the grid lines they were to accept. A gap over the active surface immediately adjacent to a grid finger involves a small loss of optical coupling into the cell in that region. Because of the large number of grid lines on a violet cell the total coupling loss is significant. Reduction of unbonded active area would be a straight forward improvement.

One unexpected problem was encountered in bonding grooved covers onto violet cells with front contact metallization applied using a photomask process. In order to use a grooved glass method it is necessary to know the location of all material projecting above the plane of the cell active surface. Grooving can be accomplished for the contact grid pattern itself but is almost impossible for random extraneous metallization. Flaws in the photomask used for the contacting operation can cause spurious bits of metal

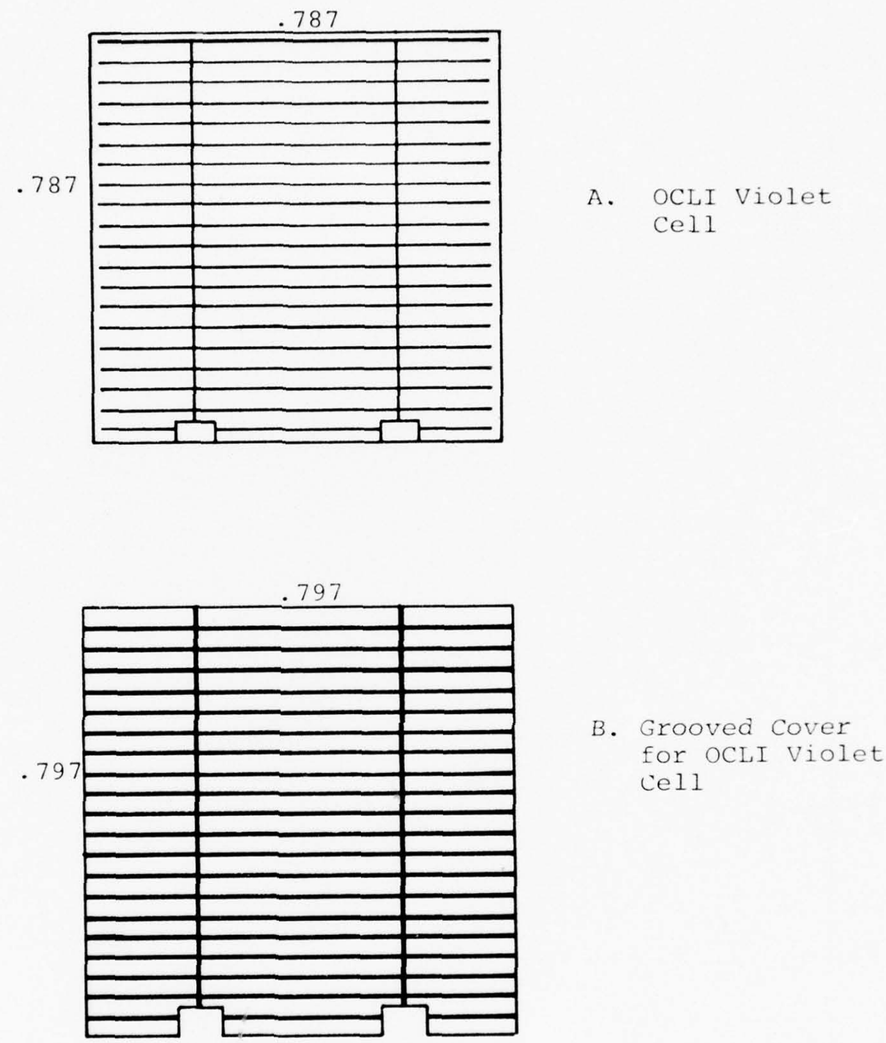


Figure 28. Configuration of OCLI Violet Cell and Grooved ESB Cover

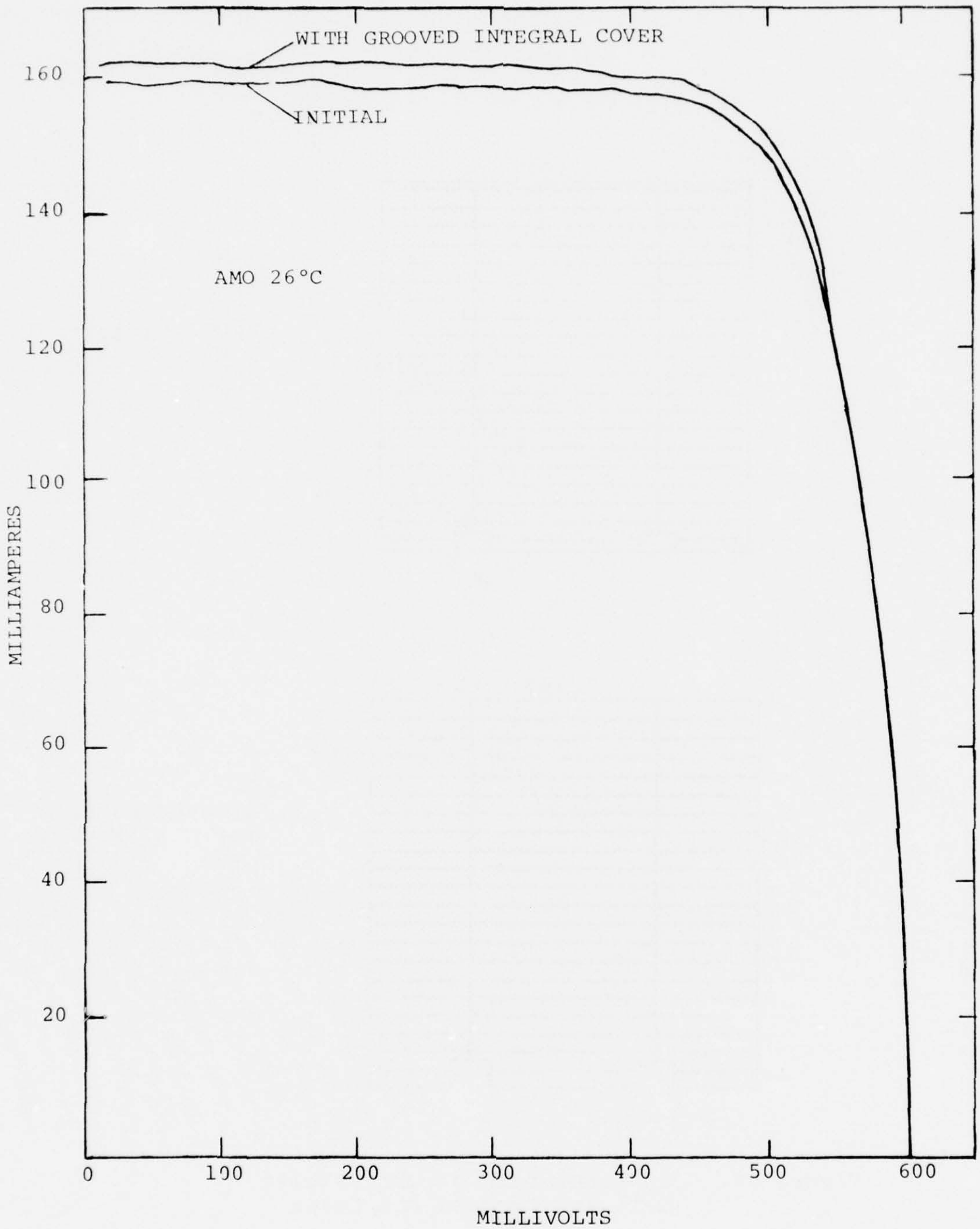


Figure 29. AMO I-V Characteristics of OCLI Violet Cell Before and After Application of Grooved ESB Integral Cover

residue to be scattered on the cell surface and these interfere with bonding of a grooved cover. Isolated small spots of stray metal cause small unbonded regions under the cover as shown in Figure 30. If sufficiently numerous, the spots can prevent a bond from being achieved over the area of the cell surface involved by preventing the required initial contact between the glass and active surface.

(e) Lithium Doped P/N Cells

Lithium can move readily in silicon at temperatures used for electrostatic bonding. If an ESB cover is to be bonded to a lithium doped solar cell, lithium in the cell will redistribute during the bonding process. An initial consideration relative to a lithium doped cell involved the possibility that availability of lithium ions from the cell surface might prevent the ESB process from working. Experimentally no problems were encountered in achieving bonds to lithium doped cells. But redistribution of the lithium profile does occur and would have to be provided for in the fabrication of lithium cells for use with ESB covers.

Two types of lithium doped cells were investigated under the program. The first group, P^+/N cells supplied by OCLI, had aluminum contacts and lithium introduced by evaporation and then diffusion. These cells developed non ohmic back contacts when subjected to the bonding process or to only the thermal environment of the bonding process. A typical I-V characteristic is shown in Figure 31. Any additional thermal treatment of these cells caused additional contact degradation. Good mechanical bonds were achieved and it is assumed that satisfactory electrical performance would also result if cells with corrected contacts were used.

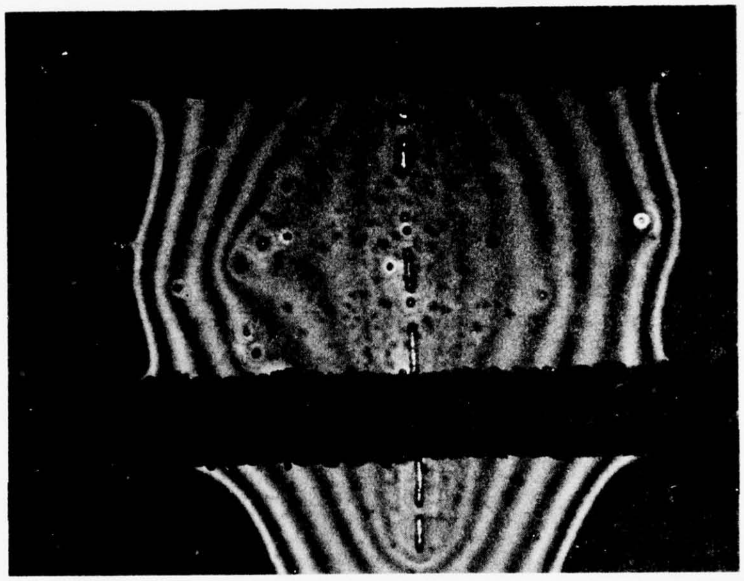


Figure 30. Bond Defect Under Grooved Cover on Violet Cell Due to Stray Metal Residue

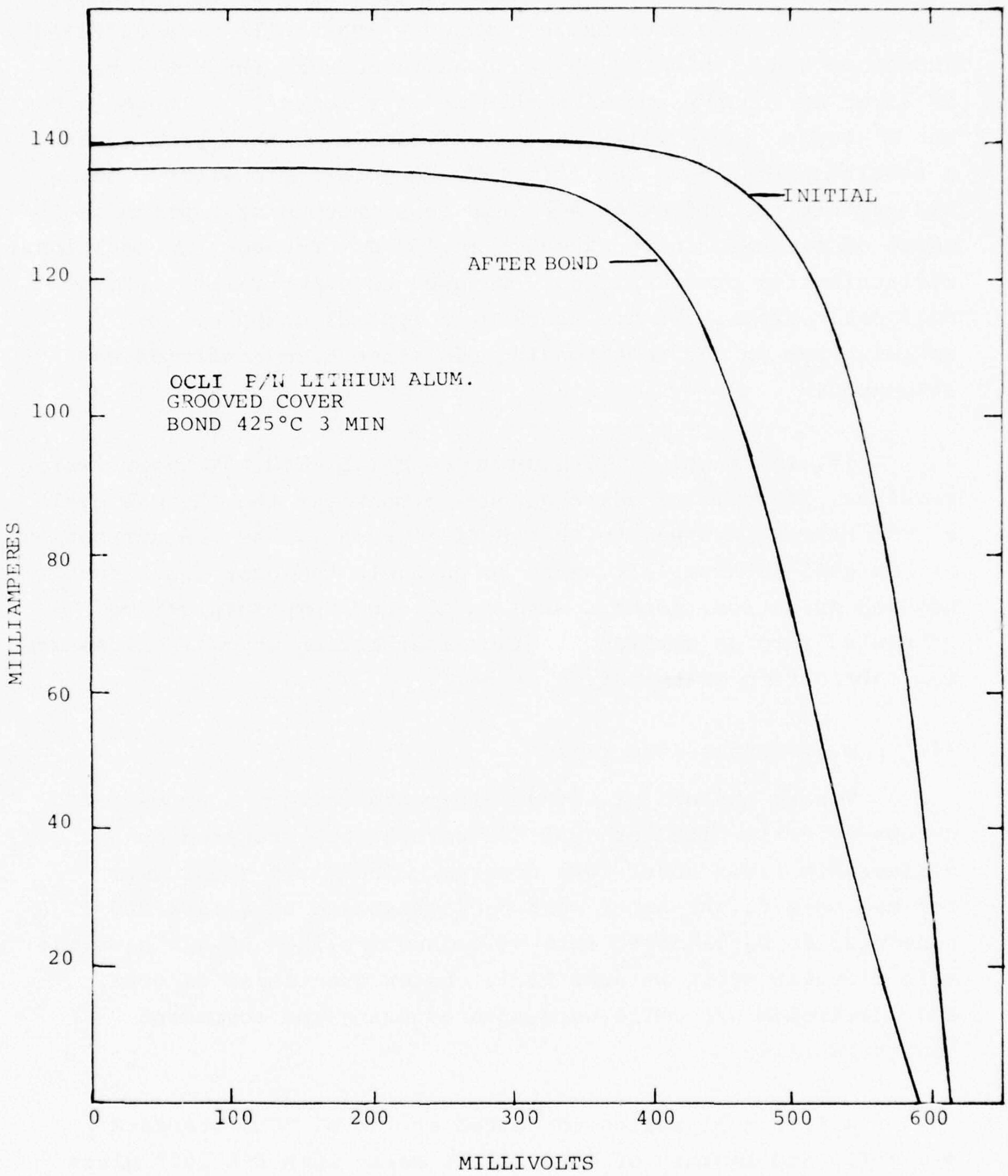


Figure 31. I-V Characteristics OCLI P/N-Li Aluminum Contact Cell

The second group of lithium doped cells was supplied by AFAPL. These were aluminum contacted P^+/NN^+ cells with diffused junctions and lithium which had been introduced through a back N^+ layer by ion implantation then redistributed[15]. Because of the N^+ layer, these cells did not develop a contact problem as a result of bonding. The cell I-V characteristic after bonding did exhibit the effect of a change in lithium distribution because of a three minute exposure at 450°C. However, an additional redistribution treatment could be used to essentially restore full cell output. Figure 32 shows a typical example. No optimization of the post bonding redistribution condition was attempted.

If, in practice, lithium doped cells with ESB covers were required, it would be advantageous to consider the thermal cycle of the bonding process to be the final step in the redistribution of the cell lithium. It would be possible to incorporate the bonding operation, perhaps with an altered temperature/time schedule, into an optimum lithium distribution which is necessary for fabrication of this type of cell.

(f) Deliverable Item Cells

Toward the end of the developmental effort a number of groups of cells with integral ESB covers were prepared as deliverable items under this program. The first group were for use on a flight experiment package aboard satellite NTS-2 scheduled to be launched into 64 degree inclined 10,900 nautical mile circular orbit in June 1977. Later quantities of OCLI and Spectrolab N/P cells were covered using the automated bonder facility.

A five cell series connected string of OCLI standard N/P cells and another of OCLI violet cells with ESB 7070 glass covers were to be included on NTS-2. OCLI provided a group of high performance violet cells for this effort and some 10 Ω-cm

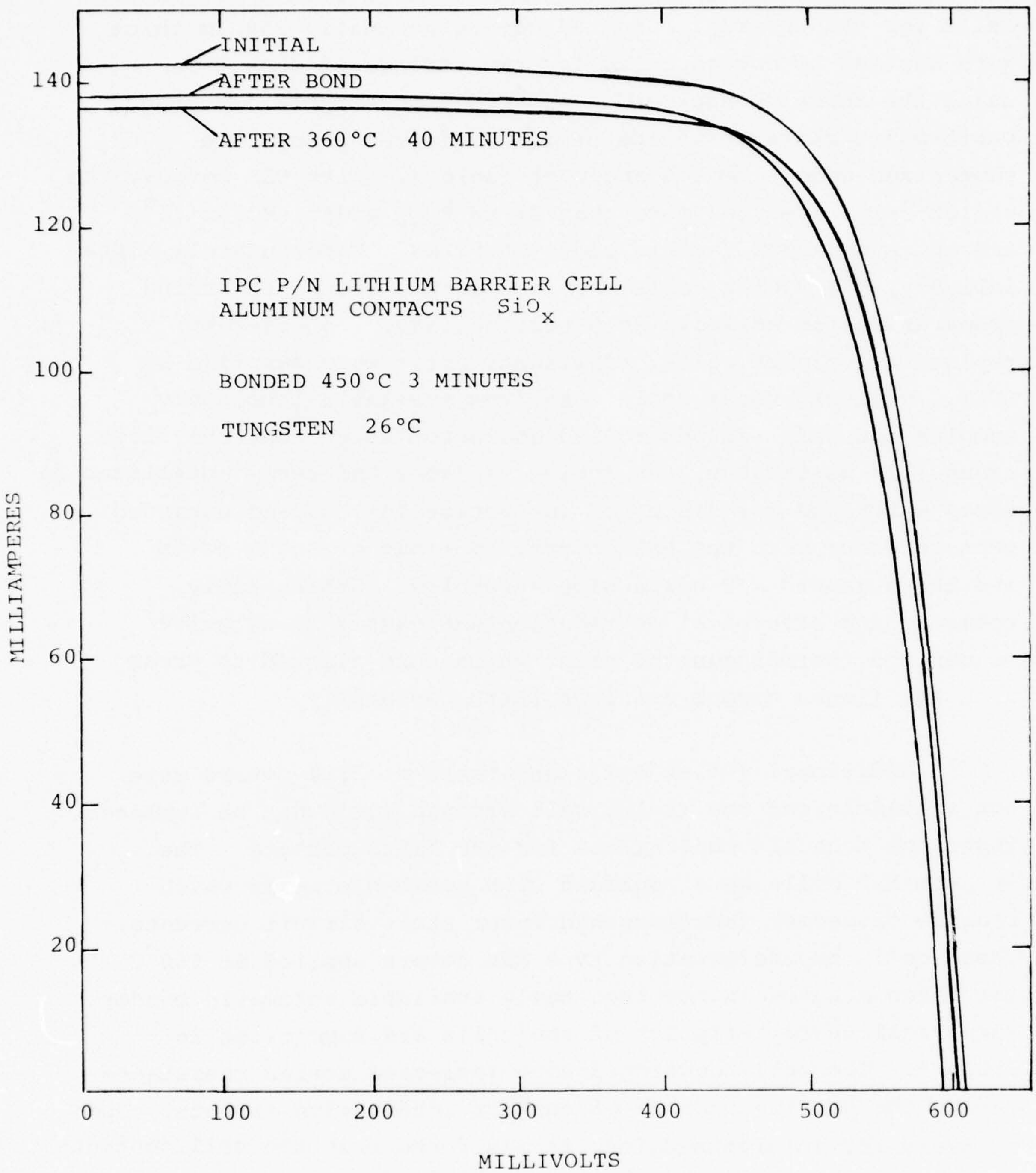


Figure 32. I-V Characteristics of Lithium Doped P/N Cell

OCLI N/P cells were available from remaining developmental cells for the program. Grooved covers nominally 250 μm thick were applied to enough cells for two strings of each type using the manual bonder and a 450°C/3 minute cycle. Average performance characteristics of the delivered groups are summarized under items A and C of Table 3. With ESB covers, the violet cells averaged more than 71 mW P_{max} under AMO at 26°C and the standard N/P cells close to 57 mW. Unfortunately, after delivery, the violet cells were accidently destroyed during preparation for assembly into test strings. In order to replace the violet cells, additional cells were supplied by OCLI. However, these cells were from available laboratory samples and had less controlled characteristics than the first group. In particular, the active surfaces had stray metallization spots which, as was discussed in Section (d), caused unbonded gaps to occur with the ESB covers. Strings of these cells and the standard N/P cells were assembled. Subsequently, cosmetic and electrical degradation was caused by adhesive primer and thermal control paint which were allowed to creep into the finger groove openings in the covers.

Additional violet cells and their special covers were not available and the violet cell strings could not be replaced under the schedule constraints for the NTS-2 package. The 10 Ω-cm N/P cells were replaced with available cells which because of deeper junctions had lower short circuit currents. These cells had deformation type ESB covers applied at 560°C for three minutes in the then newly available automatic bonder. Electrical characteristics of the cells are summarized in Table 3. The cells developed some increased series resistance during the bonding because of contact interaction effects. Upon delivery for interconnection, it was found that the cell contacts had inadequate pull strength and could not be properly interconnected. Another group, E of Table 3, was prepared using

TABLE 3. ESB COVER CELLS PREPARED FOR NTS-2.

Group	No. of Cells Del'd	Cell Type	ESB Cover	Average AMO Performance of Covered Cells			Comments
				I_{sc} (mA)	P_{max} (mW)	V_{oc} (mV)	
A. Violet Cells	11	OCLI Violet Cells for NTS-2	Grooved 7070 Applied in Manual Bonder 450°C/ 3 min.	155	71.3	603	Cells accidently destroyed prior to module base
B. Replacement Violet Cells	15	OCLI Violet Cells from laboratory stock	Grooved 7070 Applied in Manual Bonder 450°C/ 3 min.	AMO Data Not Available			Quality of covered cells questionable. Cell strings damaged during module assembly.
C. Standard N/P	18	OCLI 10 Ω-cm N/P - standard junction	Grooved 7070 Applied in Manual Bonder 450°C/ 3 min.	145	56.7	553	Cell strings damaged during module assembly.
D. Replacment N/P	14	OCLI 10 Ω-cm N/P - deep junction	Deformed 7070 Applied in Automatic Bonder 560°C/3 min.	136	52	554	Cells could not be interconnected.
E. Replacement N/P	12	OCLI 10 Ω-cm N/P - deep junction	Deformed 7070 Applied in Automatic Bonder 560°C/3 min.	135	50	552	Cells could not be interconnected.
F. Replacement N/P	14	OCLI 10 Ω-cm N/P - deep junction	Deformed 7070 Applied in Automatic Bonder	134	50.5	550	Used on flight module.

All cells 2 x 2 cm. All covers nominal 250 μm thick.

some forming gas flow into the bonder oven during the 560°C/3 minute bonding operation. These also could not be interconnected. Finally another group, F, was prepared using the forming gas flow and a 540°C/3 minute cycle. Although the contacts were still less than satisfactory the cells could be interconnected for use on the flight panel.

Before the contact adherence problem was identified on automatically bonded NTS-2 cells, quantities of OCLI and Spectrolab cells were run through the bonder to complete the experimental program. These groups, particularly the Spectrolab cells which were not sintered before bonding, were characterized after bonding by contact degradation and poor contact adherence. Performance characteristics are summarized in Table 4.

Contact problems encountered with the automated bonder are associated with inadequate control of the bonder atmosphere during the bonding cycle. Typically, the silver of a titanium-silver contact can be pulled from the surface leaving a colored oxidized titanium layer below. The flow of forming gas introduced into the bonder was inadequate to exclude oxygen from the cell positions during high temperatures and degradation resulted. A bonder modification for exclusion of ambient atmosphere is planned.

TABLE 4

PERFORMANCE CHARACTERISTICS OF FIRST CELL LOTS PROCESSED IN AUTOMATED BONDER

Cells	Quantity	Avg. Initial Performance			Avg. Change After Covering		
		I_{sc} mA	P_{max} mW	V_{oc} mV	I_{sc}	P_{max}	V_{oc}
OCLI 10 Ω-cm N/P Sintered TiAg	150	137	55	558	-3%	-9%	-1%
Spectrolab 1 Ω-cm N/P Unsintered TiAg	250	125	46	545	-1%	+7%	+9%

SECTION IV

ENVIRONMENTAL EVALUATIONS

1. SUMMARY

A number of environmental tests have been conducted on representative cells with ESB covers. Most of these tests were performed at approximately the midpoint of the program and involved cells with covers applied using the manual bonder facility. The tests included:

(i) Temperature - humidity storage
(30 days at 45°C, 95% relative humidity)

(ii) Thermal Cycling
(300 cycles from -150°C to +150°C)

(iii) Vacuum-ultraviolet Storage
(1200 hours at $<10^{-5}$ torr, 30°C with total ultraviolet exposure of 14 watt-hrs/cm^2).

(iv) Proton Irradiation
(1 MeV protons to 10^{13} cm^{-2})

(v) Electron Irradiation
(1 MeV electrons to 10^{16} cm^{-2})

Using samples covered by the automated bonder facility, a second electron irradiation and simplified thermal cycling between dry ice in alcohol and boiling water were also conducted.

Standard temperature-humidity storage and thermal cycling tests were performed in facilities at Acton Environmental Testing Laboratories, Acton, MA. Vacuum-ultraviolet storage and simplified

thermal cycling tests were conducted within Simulation Physics. Proton irradiations were performed using a Van de Graaff Accelerator Facility at KSW Electronics Inc., Burlington, MA and electron irradiations utilized a Dynamitron at Air Force Cambridge Research Laboratory, Bedford, MA. All cell performance measurements were made with a Spectrosun X-25 Mk II AMO simulator at Simulation Physics

The individual tests performed are discussed below. It is possible to generalize the results of these tests and of all experience to date regarding ESB covers on solar cells as follows:

(i) No electrostatically bonded 7070 glass cover has shown any evidence of delamination or other failure even over a small area under any environmental test condition.

(ii) Cells with integral ESB covers exhibit no tendency to degrade more rapidly due to environmental exposure than do similar cells with glued covers.

2. TEMPERATURE-HUMIDITY STORAGE

A storage test for 30 days at 45°C and 95% relative humidity was conducted on a number of glass slide samples and on OCLI 10 Ω-cm N/P cells with 7070 ESB covers applied using the manual bonder. Similar cells with glued 7070 glass and 7940 fused silica covers and without covers were also subjected to the same environment. Cells with both titanium-silver and titanium-palladium-silver contacts and with SiO_x and Ta_2O_5 antireflective coatings were utilized. No major variations were observed between cell types and because of the small sample quantities involved, performance data were averaged over all cells.

The physical effects of the storage environment included some weathering of cover glass materials and oxidation of contacts. Weathering was significant on 7070 glass and also to a lesser degree on 0211 Microsheet glass but was not discernible on 7940 fused silica. Optical measurements on glass samples and electrical measurements on covered cells indicate that the weathering, which is a surface corrosion effect, causes some scattering of incident light but does not measurably reduce total transmission. Oxidation of both titanium-silver and titanium-palladium-silver contacts in this test was primarily cosmetic. Three cells with aluminum contacts were also subjected to the test environment and experienced sufficient contact oxidation to prevent post-test electrical measurements. Treatment of the aluminum contact surfaces with a potassium hydroxide solution allowed measurements to be made which confirmed essentially initial output characteristics.

Among 15 cells in the test with integral 7070 glass covers, only one showed any evidence of local physical change in or near the cell-cover interface as a result of the test environment. The single exception was an N/P cell with SiO_x antireflective coating, titanium-silver contacts and plastically deformed ESB cover. The cell developed small area (1 mm diameter) separations under the cover at the extreme ends of 5 of its 6 grid fingers. The separations were metallic in appearance indicating that the SiO_x coating had detached from the silicon surface. No other cells under any tests have shown similar effects even on a microscopic scale and it is believed that the AR coating in the particular cell was defective.

Electrical measurements from the OCLI N/P cells with TiAg and TiPdAg contacts have been combined for each cover type and are summarized in Table 5. The cells with integral 7070 covers performed as well as or better than similar bare cells and cells

TABLE 5

TEMPERATURE-HUMIDITY TEST DATA SUMMARY
AFTER 30 DAYS AT 45°C, 95% RELATIVE HUMIDITY

COVER TYPE	NO. OF CELLS	AVERAGE % CHANGE		
		I_{sc}	V_{oc}	P_{max}
Integral 7070 - grooved	10	+0.3	-0.4	-1.2
Integral 7070 - deformed	2	+1.5	0	-0.5
Glued 7070	3	-1.7	-0.4	-2.0
Glued 7940	4	-1.1	+0.7	0
None	8	-0.4	0	-1.3

All Cells OCLI N/P - Integral covers on Manual Bonder

TiAg or TiPdAg Contacts

SiO_x or Ta_2O_5 AR Coatings

AMO 26°C

with glued 7070 covers. The data suggest absence of significant degradation mechanisms for the integral cover in the temperature-humidity test environment.

3. THERMAL CYCLING

A thermal cycling test was performed involving a total of 300 cycles from -150°C to +150°C completed at a rate of approximately one cycle per hour. Low temperature nitrogen gas was used to reduce test chamber temperature to the lower extreme and electrical heaters were employed to return to the higher limit. Atmosphere in the unsealed chamber was mainly residual nitrogen but did include some leakage which resulted in a degree of contact oxidation and minor moisture marking of exposed surfaces.

The test included OCLI N/P cells with titanium-silver and titanium-palladium-silver contacts. Bare cells, cells with ESB 7070 covers from the manual bonder and cells with glued 7070 and 7940 covers were used. None of 17 integrally covered cells developed any physical defects involving their covers. Some cells with glued covers did develop regions of cell-cover delamination. Glass samples also included in the test exhibited no changes in optical transmittance. Electrical performance change data are summarized in Table 6. The integrally covered cells showed no performance deficiencies through this cycling test.

An abbreviated thermal shock test was conducted on representative cells with ESB covers applied using the automatic bonder. For this simple test, cells were sealed in plastic bags which were cycled 50 times between liquid nitrogen and boiling water. As has been discussed earlier in this report, the cells for this test which came from the automatic bonder had unsatisfactory contacts after bonding. The results of this thermal cycling test reflect these contact problems.

TABLE 6

THERMAL CYCLE TEST DATA SUMMARY

AFTER 300 CYCLES FROM -150°C TO +150°C

COVER TYPE	NO. OF CELLS	AVERAGE % CHANGE		
		I_{sc}	V_{oc}	P_{max}
Integral 7070 - grooved	9	-1.0	-0.2	-1.7
Integral 7070 - deformed	3	-0.5	-0.2	-1.8
Glued 7070	4	-1.5	-1.5	-2.6
Glued 7940	4	0	-0.8	-1.9
None	8	-1.1	-0.1	-1.9

All Cells OCLI N/P - Integral Covers on Manual Bonder

TiAg or TiPdAg Contacts

SiO_x or Ta_2O_5 AR Coatings

AMO 26°C

None of the cells in the 50 cycle thermal shock test experienced any physical changes involving the ESB covers. The OCLI cells showed no performance losses during the test but the Spectrolab cells, because their contacts had not been sintered prior to covering in the automatic bonder, exhibited increasing series resistance. Figure 33 shows example I-V characteristics from one of the Spectrolab cells in the test. As could be expected, the nonadhering contacts on these cells worsened as a result of the repeated thermal shock. Again, it can be anticipated that corrective modification to the environment of the automated bonder would eliminate this problem.

4. VACUUM-ULTRAVIOLET STORAGE

A vacuum-ultraviolet storage test was performed in a water cooled vacuum system which allowed samples under test to temperature stabilize at 30°C. An oil diffusion pump system with liquid nitrogen cooled baffle maintained continuous vacuum well below 10^{-5} torr. An automatic liquid nitrogen refill control maintained baffle temperature to minimize backstreaming of diffusion pump oil. A General Electric UA-2 250 watt mercury vapor lamp was mounted outside the vacuum system and samples under test were illuminated through a 6 inch diameter fused silica window. Actual ultraviolet intensity at the test location was measured using an Eppley thermopile in conjunction with a set of filters. Ultraviolet intensity upon test samples was measured to be 10.3 mW/cm^2 between 220 and 440 nm with total spectral irradiance of 53 mW/cm^2. The one solar constant AMO spectrum includes 11.8 mW/cm^2 of ultraviolet below 400 nm(16) so that this ultraviolet exposure test came close to approximating real time. Figure 34 compares the spectral distribution of the Thekaekara AMO curve in the ultraviolet to manufacturer's data on the mercury vapor lamp distribution. The ultraviolet exposure test was interrupted for sample measurements after the corrected equivalent of 600 hours of AMO UV exposure and the test was terminated after the equivalent of 1200 hours. None of the

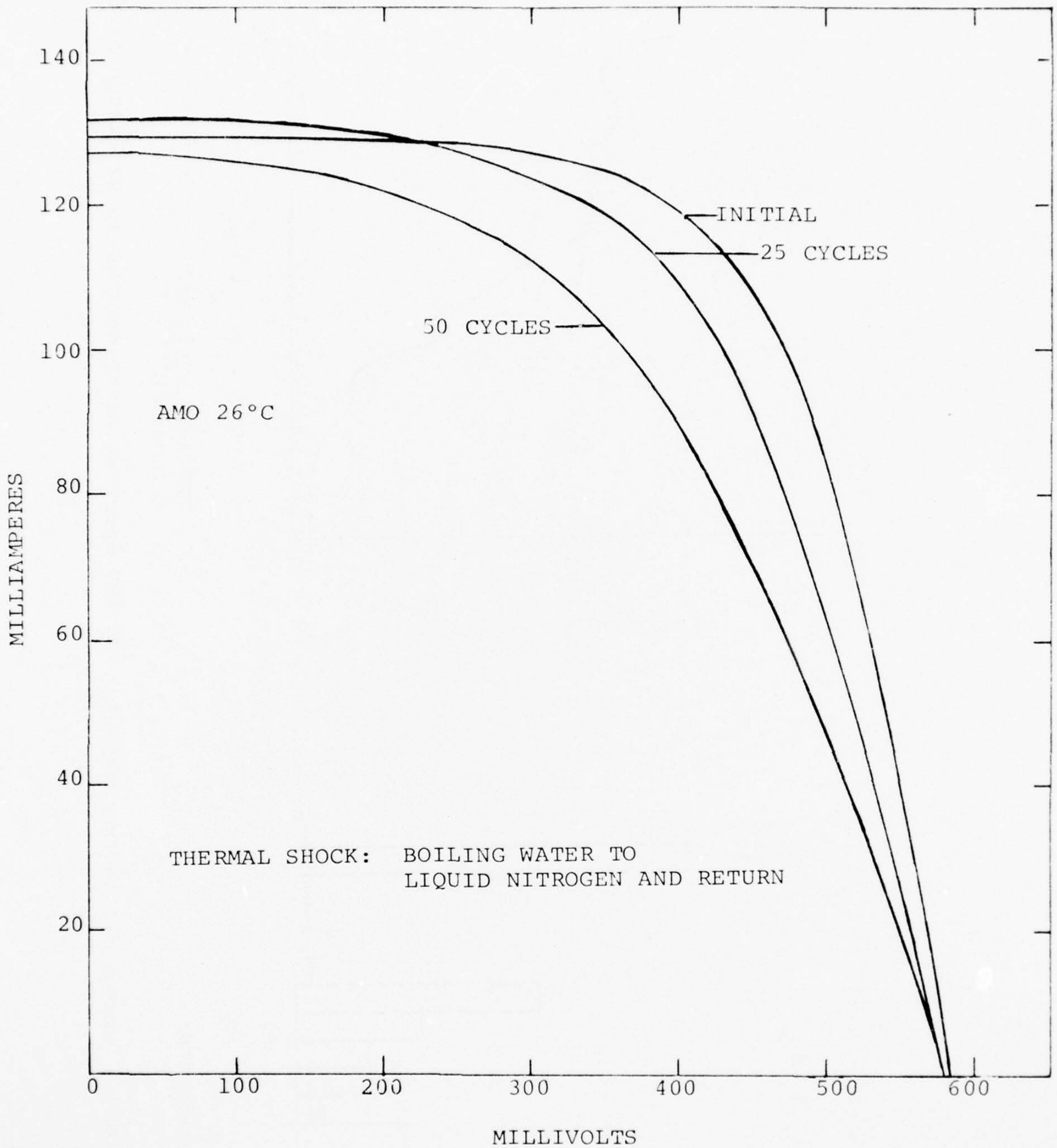
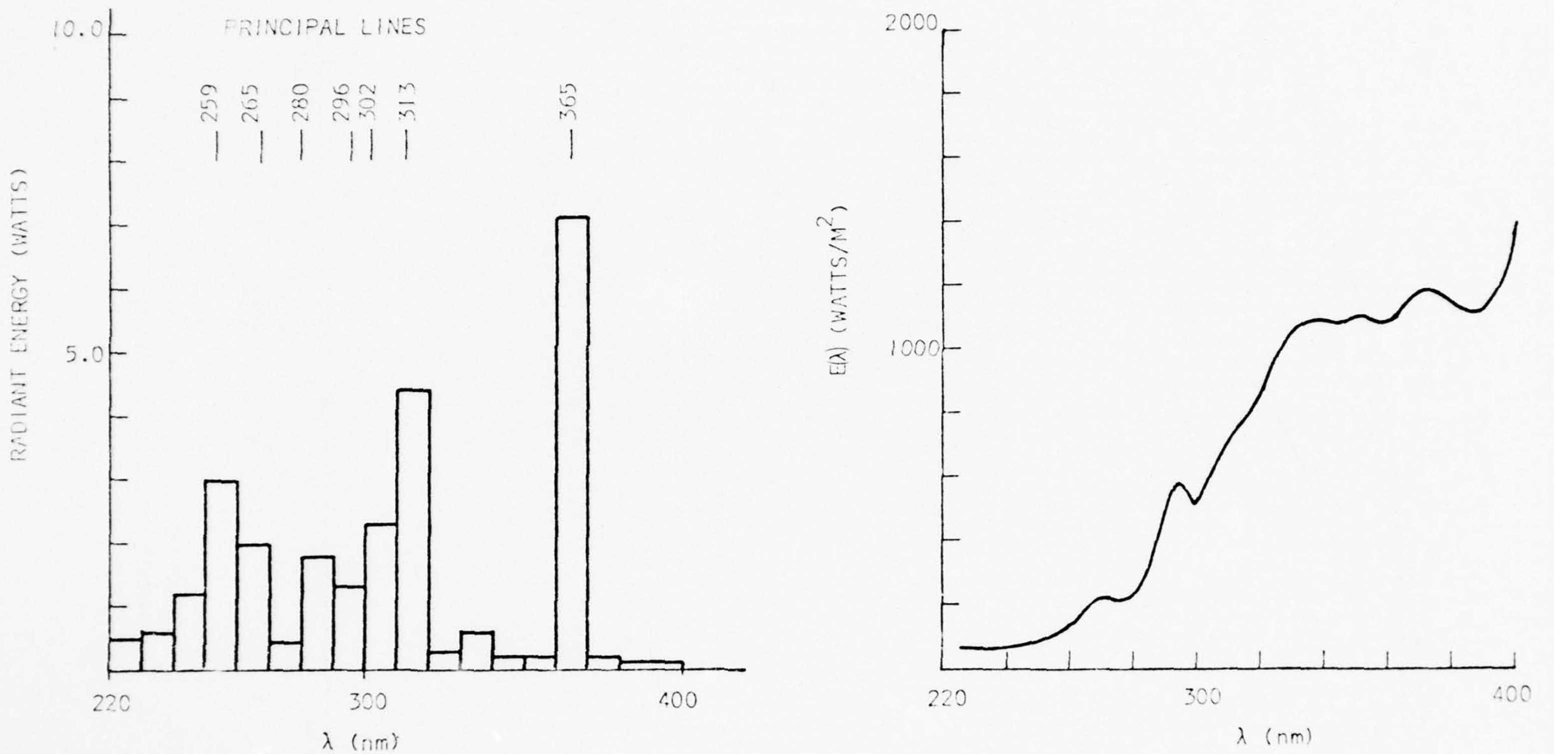


Figure 33. Effect of Thermal Shock Test on Spectrolab Cell With ESB Cover From Automatic Bonder



UA-2 Hg Lamp Spectrum

AMO Solar STD Curve
Reference 12

Figure 34. Comparison of Mercury Lamp and AMO Spectral Distributions in 220-440nm Band

solar cells or cover glass samples showed any visible changes after 600 hours. After 1200 equivalent hours, some minor yellowing of 7070 glass slides was evident. Optical transmission data was given in Figure 3b.

Table 7 summarizes electrical performance averages after 600 and 1200 equivalent hours. All of the integral cover samples in this test had titanium-silver or titanium-palladium-silver contacts but glued cover samples were all of similar OCLI N/P cells with aluminum contacts. Integral covers were applied in the manual bonder. Bare cell data are included in Table 7 for both contact types. It can be seen that the integrally covered cells showed appreciably less degradation than cells with glued 7940 fused silica covers which included 400 nm cut-on filters. Glued 7070 glass covers which did not include ultraviolet rejection filters allowed lamp UV to reach the Sylgard 182 silicone resin adhesive and the cells involved exhibited large current losses. The degradation experienced by the cells having glued 7940 covers with UV rejection filters has not been explained.

5. 1 MeV PROTON IRRADIATION

Proton irradiations were performed on groups of integrally covered OCLI N/P cells. All covers were 300 μm thick 7070 glass. Each sample was irradiated to only a single fluence step. Uncovered cell front contact bars were protected with 75 μm thick aluminum foils during irradiations. Test data are summarized in Table 8. Any cell exhibiting measurable performance change was found under microscopic inspection to have small exposed surface area due to cover misalignment. The 7070 glass covers are judged to provide completely adequate protection against proton damage.

6. 1 MeV ELECTRON IRRADIATION

Using a Dynamitron at Air Force Cambridge Research Laboratory, cell and glass samples were subjected to 1 MeV

TABLE 7

ULTRAVIOLET-VACUUM STORAGE TEST DATA SUMMARY

AFTER 600 AND 1200 EQUIVALENT AMO HOURS AT 30°C, $<10^{-5}$ TORR

COVER TYPE	NO. OF CELLS	AVERAGE % CHANGE 600 HRS.			AVERAGE % CHANGE 1200 HRS.		
		I_{sc}	V_{oc}	P_{max}	I_{sc}	V_{oc}	P_{max}
Integral 7070 - grooved	7	-0.2	0	-0.3	-2.1	-0.7	-3.1
Integral 7070 -deformed	2	-0.4	0	-0.2	-2.3	-0.6	-3.3
Glued 7070*	2	-8.2	-0.2	-7.2	-14.9	-1.1	-14.0
Glued 7940 with 440 nm cut-on filter*	2	-4.6	0	-3.5	-5.7	-0.6	-5.6
None	3	-0.8	0	-0.9	-1.3	-0.5	-2.1
None*	2	0	0	+0.4	-1.1	-0.9	-2.9

All Cells OCLI N/P - Integral Covers on Manual Bonder

TiAg or TiPdAg Contacts, except *Aluminum

SiO_x or Ta_2O_5 AR Coatings

AMO 26°C

TABLE 8

1 MeV PROTON IRRADIATION DATA SUMMARY
FOR INTEGRAL COVER CELLS

1 MeV PROTON FLUENCE	GROOVED INTEGRAL COVERS			DEFORMED INTEGRAL COVERS		
	NO. OF CELLS	% CHANGE		NO. OF CELLS	% CHANGE	
		I_{sc}	P_{max}		I_{sc}	P_{max}
10^{10} cm^{-2}	3	0	-0.1	2	0	0
10^{11}	3	0	-0.1	1	0	0
10^{12}	3	-0.2*	-0.6*	2	0	0
10^{13}	3	0	-0.5	2	-0.4*	-1.2*

All Cells OCLI N/P - Integral covers on Manual Bonder

TiAg or TiPdAg Contracts

SiO_x or Ta_2O_5 AR Coatings

* Included cell or cells with small unprotected surface areas due to cover misalignment.

AMO 26°C

electron fluences of 3×10^{14}, 1×10^{15}, 3×10^{15} and 1×10^{16} cm^{-2}. Each sample was exposed to all levels. Cells were OCLI 10 ohm-cm N/P. Covers were 300 μm ESB 7070 applied using the manual bonder, glued 300 μm 7940 fused silica or glued 300 μm 0211 Microsheet.

The 7070 and 0211 glass samples showed significant darkening under the electron irradiation. Transmittance curves for 10^{15} and 10^{16} electrons/cm^2 fluences are shown in Figures 35a and 35b respectively. In the case of the 7070 glass the darkening was more serious than has been measured on other 7070 material(7). Several laboratories have observed varying degrees of radiation darkening in 7070 glass coming from different production runs at Corning Glass Works. The material used in the present program experienced more darkening than is thought to be typical of 7070. The transmittance data in Figures 35a and 35b indicate that darkening of the 7070 glass was less than that of the 0211 at lower fluences but was more than that of 0211 at high fluence. Figure 36 shows comparable data from an earlier evaluation of radiation darkening in which the particular lot 7070 material was superior at all levels. In the present program, as was discussed in Section 2.3, although the 7070 darkened under electron irradiation, it underwent rapid, effective bleaching when exposed to ultraviolet illumination following irradiation. As was shown in Figure 3a, transmittance was restored to almost pre-irradiation level by the equivalent of approximately 48 hours of AMO solar constant ultraviolet.

As a result of darkening of the 7070 glass, cells with ESB 7070 covers degraded under electron irradiation more rapidly than did similar bare or glued fused silica covered cells. Averaged normalized I_{sc} and P_{max} data are presented in Table 9. Following the final irradiation step, half of the cells with integral 7070 covers were exposed to the equivalent of 14 hours of solar constant

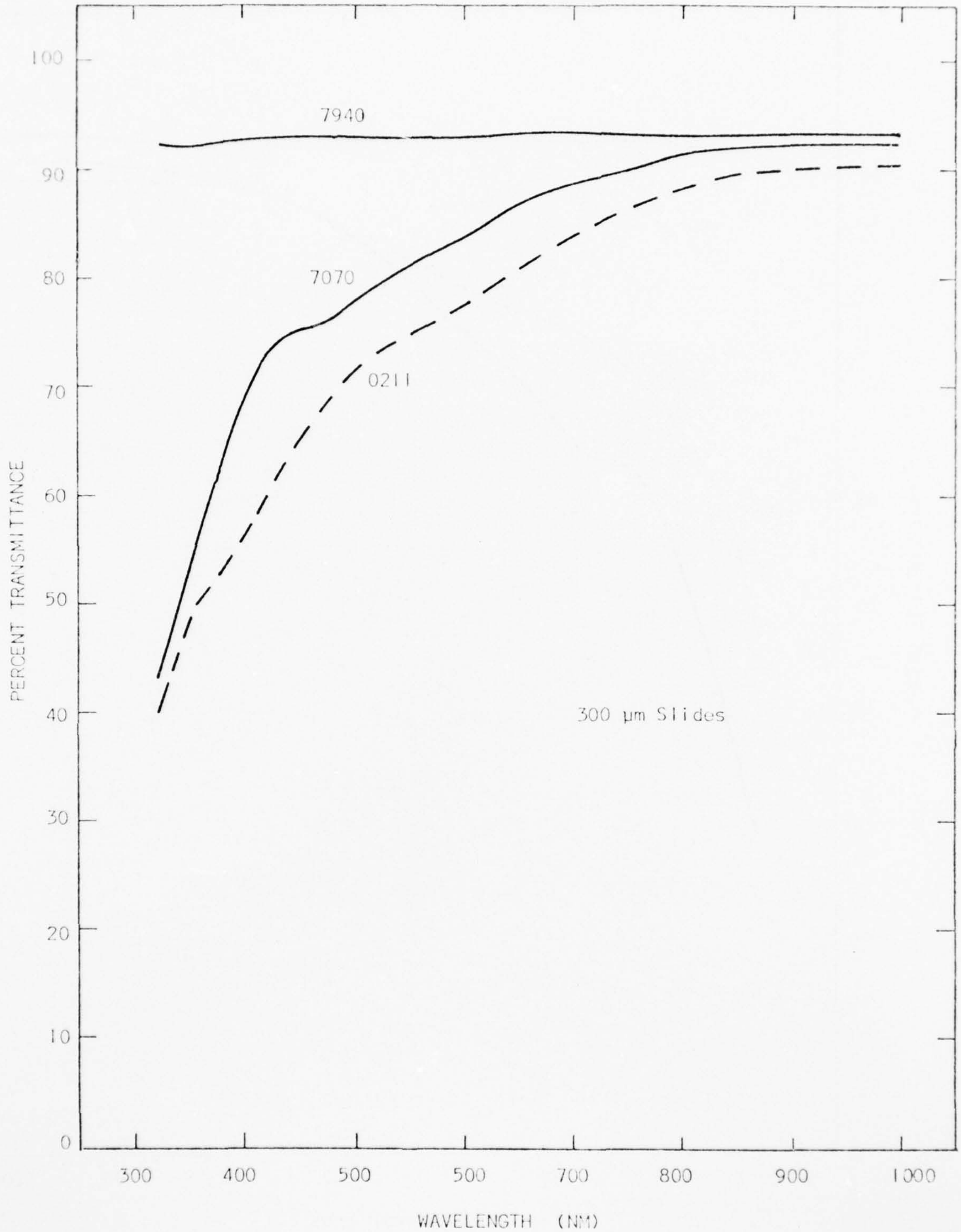


Figure 35a. Transmittance of Glass Slides After 10^{15} cm^{-2} Electron Irradiation.

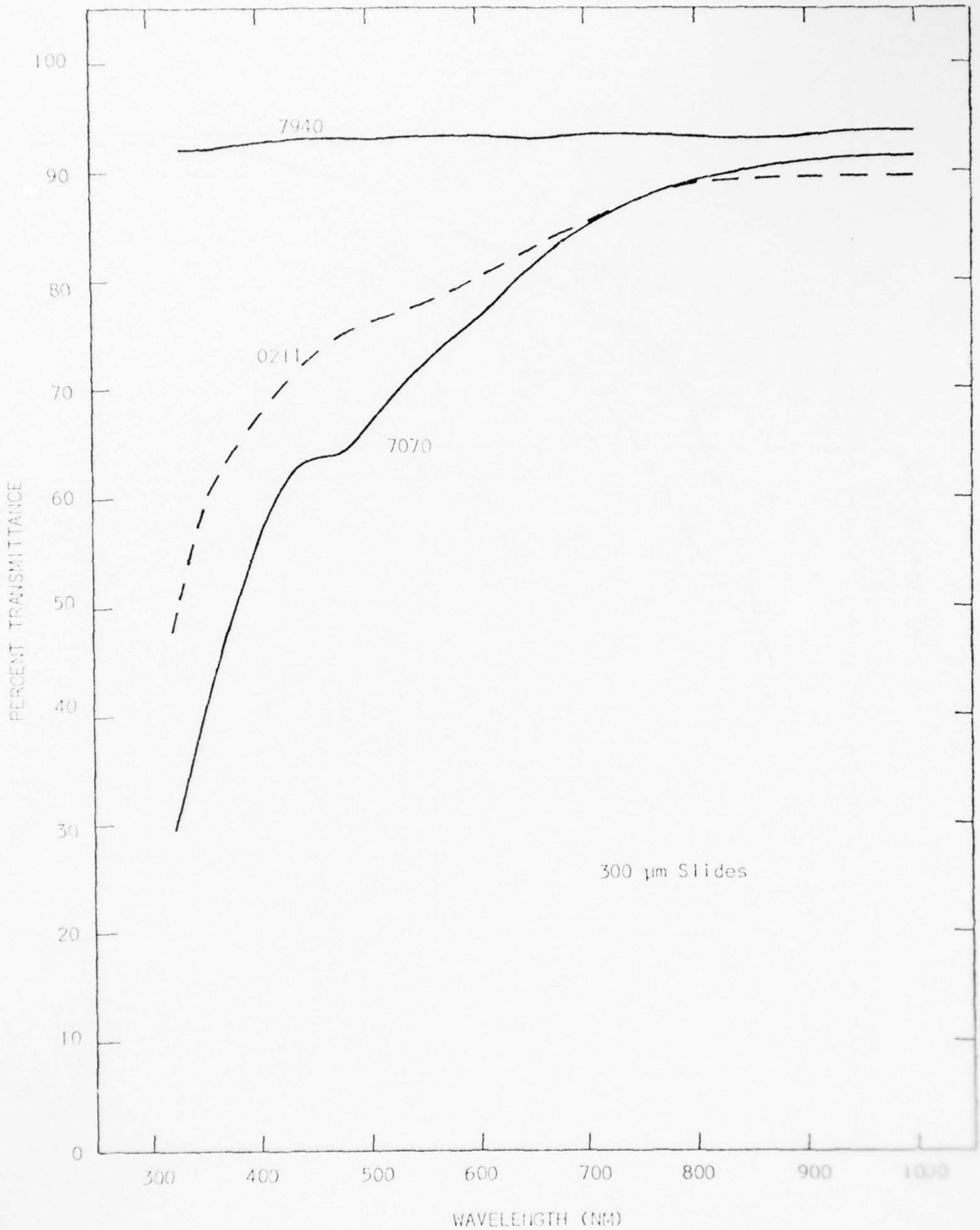
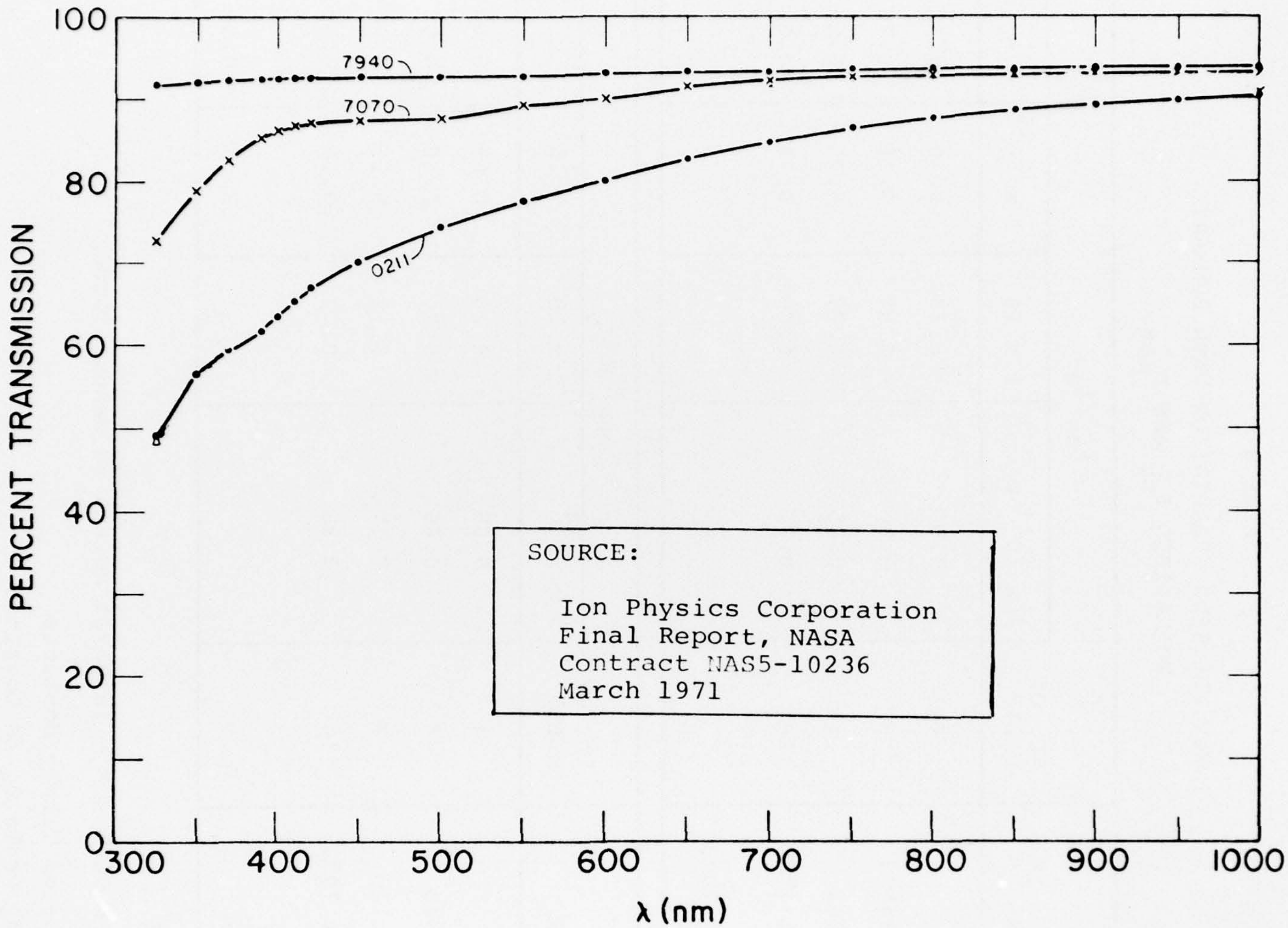


Figure 35b Transmittance of Glass Slides After 10^{16} cm^{-2} Electron Irradiation.

AD-A043 854 SIMULATION PHYSICS INC BEDFORD MA F/G 10/2
STRESS FREE APPLICATION OF GLASS COVERS FOR RADIATION HARDENED --ETC(U)
MAY 77 A R KIRKPATRICK, W S KREISMAN F33615-74-C-2001
UNCLASSIFIED AFAPL-TR-77-28 NL

2 OF 2
AD
A043854

END
DATE
FILMED
9-77
DDC



Transmission of 0.006" Slides After 5×10^{15} 1 MeV Electrons.

Figure 36. Transmittance Data on Irradiated Glasses From Previous Study

TABLE 9

1 MeV ELECTRON IRRADIATION DATA SUMMARY

NORMALIZED I_{sc} AND P_{max}

COVER	NO. OF CELLS	I_{sc}/I_{sc_o}			
		3×10^{14} e/cm^2	1×10^{15}	3×10^{15}	1×10^{16}
None	4	0.90	0.83	0.79	0.71
Glued 7940	4	0.90	0.84	0.78	0.70
Glued 0211	3	0.85	0.79	0.75	0.68
Integral 7070	10	0.87	0.80	0.74	0.64
Integral 7070 after UV	5				0.71

COVER	NO. OF CELLS	P_{max}/P_{max_o}			
		3×10^{14}	1×10^{15}	3×10^{15}	1×10^{16}
None	4	0.85	0.76	0.69	0.60
Glued 7940	4	0.86	0.76	0.68	0.56
Glued 0211	3	0.80	0.72	0.66	0.56
Integral 7070	10	0.82	0.73	0.65	0.54
Integral 7070 after UV	5				0.59

AMO 26°C

All Cells OCLI N/P - Integral covers on Manual Bonder

TiAg or TiPdAg Contacts

SiO_x or Ta_2O_5 AR Coatings

UV (~150 mW-hrs/cm^2 of <400 nm) under vacuum at 30°C and were then retested. Output performance increased to approximately the bare cell level. Normalized maximum power data averages are plotted in Figure 37.

A second electron irradiation was performed at the end of the program using OCLI and Spectrolab cells covered in the automated bonder. The same test facility and conditions were employed. As in the first irradiation, no mechanical defects were produced. Performance data from the OCLI cells were similar to those from the first test. Because of the contact problems, electrical data on the Spectrolab cells were inconsistent and have been disregarded.

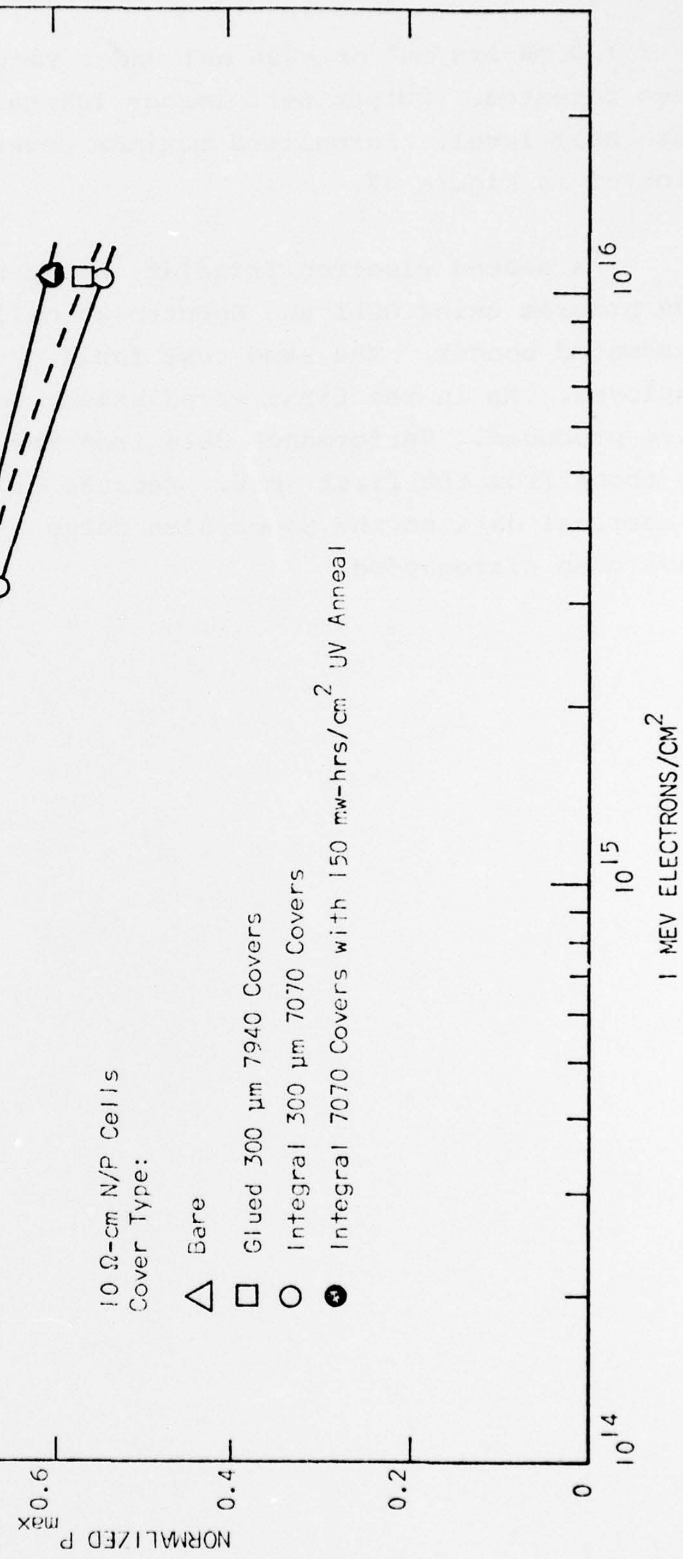


Figure 37. Normalized Maximum Power vs. Electron Fluence

SECTION V
CONCLUSIONS

This program has resulted in the development of electrostatic bonding for integral attachment of protective covers to spacecraft solar cells. Fast, simple and inherently inexpensive procedures have been identified for applying electrostatically bonded covers onto silicon solar cells. The electrostatic bond, once correctly formed is totally reliable and has no known failure modes.

It is absolutely essential that expansion characteristics of the glass used for the ESB cover must match that of silicon, otherwise the integrally covered cell will be left in a severely stressed and impractical condition. Other important considerations in the selection of the cover material are (i), stable optical transmittance resistant to permanent degradation by exposure to ionizing radiations and (ii), adequately low viscosity at temperatures compatible with the thermal limitations of the silicon solar cell. Among commercially available products, Corning type 7070 borosilicate glass has been selected as best for ESB cover purposes.

The most difficult considerations in utilizing ESB covers relate to the mechanics of performing the bonding process and to interactions of the process with the solar cell structure and its performance. The primary problem concerns the metallization pattern on the solar cell surface. The ESB cover slide can be grooved to provide space for the grid pattern or the glass can be plastically deformed around the contact metallization by the electrostatic forces. Grooved covers can be applied at approximately 450°C for 3 minutes while deformation type covers require over 500°C. Use of grooved covers demands that the cell grid pattern

be reproducible and consistently positioned on the cell surface and that no stray metal residue be present on the active surfaces. Deformation must be considered more practical than grooving but deformation does place additional requirements upon thermal stability of the solar cells. It has been found that good control of the gas environment is required, particularly at higher temperatures necessary for deformation bonds. Much of the work done under the program was plagued by inadequate ability to control residual atmosphere in the bonder. Satisfactory correction of this problem should allow temperatures somewhat higher than 560°C to be utilized for many cell types and would allow plastic deformation covers to be easily applied with few constraints upon the cell grid patterns.

ESB 7070 covers have been successfully applied to many cell types including production type N/P cells, violet cells and cells with aluminum contacts or lithium doping which would normally be considered thermally fragile. It has been demonstrated that integral covers of virtually any thickness can be applied to high performance solar cells without degrading cell characteristics. It has been shown that performance of the integrally covered cell should equal and probably exceed that of a similar cell with glued cover.

Two bonder facilities were developed for purposes of this program. The first unit had very limited throughput capability but did result in technically satisfactory integrally covered cells. A second bonder was developed to demonstrate that the ESB process could be performed on a fully automated basis. The facility demonstrated a capability for bonding covers to 60 cells per hour. Because of ambient atmosphere interactions with solar cells in process in this bonder, problems were encountered with cell contacts. A facility modification will be required for correction.

Under environmental testing, ESB covers have exhibited complete absence of physical failure modes. ESB covered cells except those with degraded contacts from the automated bonder, generally performed as well as or better than similar cells with glued covers under standard environmental test conditions. Integral 7070 glass covers provide fully adequate protection against 1 MeV protons. Under 1 MeV electron irradiation, the 7070 glass has been observed to darken but is effectively bleached by the ultraviolet component of the Air Mass Zero solar spectrum. Some production lot variability of the darkening characteristics of 7070 glass is believed to occur, the best material being very good.

The advantages to result from ESB integral covers are major. Elimination of the coverglass adhesive, and in turn the need for an ultraviolet rejection filter, makes available additional cell response from the normally rejected component of the solar spectrum. Optical losses associated with the adhesive will be eliminated. ESB covers will be characterized by extremely good, perhaps even total, reliability under severe environments. It will be possible to produce ESB covered cells with thermal stability to well beyond 500°C for purposes of laser hardness. The ESB process is inherently simple and fully automatable and has strong prospects for reducing glass protection costs to a fraction of those presently associated with glued covers.

Development of the ESB Cover technology has been very successful. Representative cells with ESB covers have shown excellent performance and environmental stability. Problems still exist with utilization of the ESB process but solutions are available. Continued development will broaden process application to other cell types and will improve the production technology.

ACKNOWLEDGEMENT

Many individuals have made important contributions to this program. Espceially appreciated has been support from Ken Ling and Peter Iles of OCLI, from John Scott-Monck of Spectrolab, from AFAPL Project Engineers John Green and Cecil Stuerke and from Ella Cumming and Denis Rockwood of Simulation Physics.

REFERENCES

(1) NASA Contract NAS5-21510, Heliotek.

(2) Air Force Contract F33615-68-C-1198, Heliotek.

(3) Air Force Contract F33615-70-C-1619, Heliotek.

(4) NASA Contract NAS5-10319, Texas Instruments.

(5) ESRO Contract 810/69/AA, Electrical Research Association, England.

(6) ESRO Contract 1407/71/AA, Electrical Research Association, England.

(7) NASA Contract NAS5-10236, Ion Physics Corporation.

(8) Air Force Contract F33615-67-C-1158, Ion Physics Corporation.

(9) NASA Contract NAS5-3857, Hoffman Electronics.

(10) Air Force Contract F33615-71-C-1656, General Electric.

(11) Wallis, G., "Direct-Current Polarization During Field-Assisted Glass - Metal Sealing", 71st Annual Meeting, American Ceramic Society, Washington, DC, May 1969.

(12) P. R. Mallory and Company, Burlington, MA.

(13) Goldhammer, L. J. "The ATS-6 Solar Cell Experiment After Six Years in Synchronous Orbit" , Twelth Photovoltaic Specialists Conference, Baton Rouge, November 1976.

(14) Private Communication, L. W. Slifer, Goddard Space Flight Center, Nov. 1976.

(15) Air Force Contract F33615-70-C-1491, Ion Physics Corporation.

(16) Thekaekara, M. P., "Extraterrestrial Solar Spectrum, 3000-6000 Å at 1-Å Intervals", Appl. Optics, 13, No. 3, 518, March 1974.

☆U.S.Government Printing Office: 1977 — 757-001/19